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(54) Broadband cholesteric optical device, polariser, filter, Liquid crystal device and polarising beam-splitter

(57) A broadband cholesteric optical device such as a polariser or spectral filter comprises a broadband cholesteric layer 1, for instance of the graded pitch type such that the cholesteric pitch increases monotonically from one surface 2 of the film 1 to the other 3. In order to improve the off-axis performance, a compensator is provided in the form of a positive birefringence film 8 whose optic axis is substantially perpendicular to the film. Another negative birefringence film 9 whose optic axis is also perpendicular to the film may also be provided.

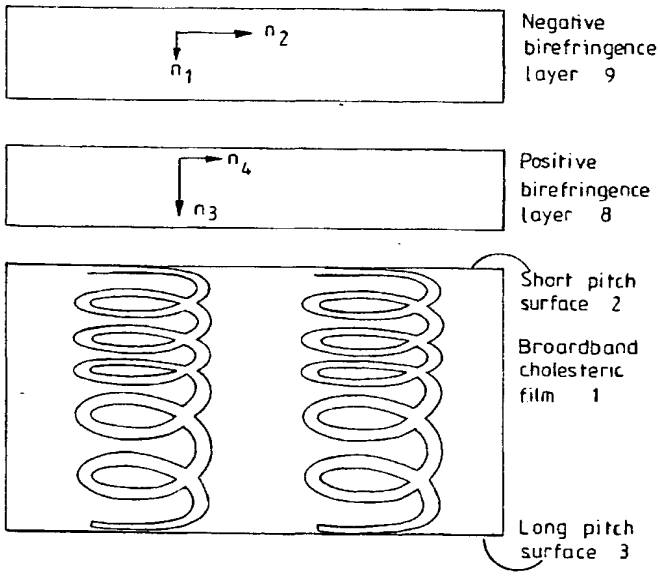

FIG. 10

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Description

The present invention relates to a broadband cholesteric optical device, for instance for use in polarisers, filters, liquid crystal devices and polarising beam-splitters. Such devices may be used in displays such as liquid crystal displays and as colour or notch filters. Such devices may also be used in head mounted displays, optical and electronic measuring and sensing systems, compensators and for high flux applications.

As is well known in the art, a cholesteric liquid crystal is one in which the director rotates through the material, forming a helical structure. The term "cholesteric" is synonymous with "chiral nematic".

EP 0 720 041 discloses patterned cholesteric colour filters and polarisers which comprise several layers which are active in different defined spectral bands.

EP 0 634 674 discloses a wide spectral and angular bandwidth rear polariser for direct view displays. The broadband polariser is made using high birefringence cholesteric materials or by using stacks of lower birefringence cholesteric films.

EP 0 606 940 discloses a broadband cholesteric polariser which is made using a combination of ultraviolet (UV) intensity profile and diffusion to expand the polariser bandwidth. The intensity profile results from using a polymerising wavelength in a range where the maximum of the sum of the absorptions of the cholesteric material and the photoinitiator exists. Alternatively, an appropriate UV absorbing dye is added to the cholesteric mixture. The polariser comprises a graded pitch structure which varies monotonically from one surface of the polariser to the other.

Although not shown, similar off-axis birefringence effects occur if a thick cholesteric layer is provided after each reflecting layer.

"Optics of cholesteric liquid crystals", V.A. Belyakov et al, Sov. Phys. Usp. 22(2), pp 63-88, Feb. 1979 and "Optical properties of the interface between a twisted liquid crystal and an isotropic transparent medium" G. Joly et al, J Optics, vol 25 pp 177-186 (1994) disclose that, for a single pitch cholesteric film, the polarisation state of reflected and transmitted light has a complex dependence on wavelength and angle of illumination. For graded pitch cholesteric films providing wider reflection bandwidths, the angular dependence is more complex but has not been studied. "Theory of light reflection by cholesteric liquid crystals possessing a pitch gradient" L.E. Hajdo et al, J.Opt. Soc. Am. vol 69, No. 7, July 1979 considers only normal incidence.

WO96/02016 discloses a backlight illumination system for a liquid crystal device (LCD) comprising a broadband cholesteric polariser. This patent discloses that improved off-axis performance may be achieved by orienting the cholesteric liquid crystal polymer (CLCP) polariser such that the largest pitch is closest to the illumination source. Also, a negative birefringence quarter wavefilm may be used to provide a further improvement to the off-axis performance as well as to convert light to a linearly polarised state.

It is known to use compensators in LCDs in order to reduce or eliminate the unwanted effects of birefringence. Various types of compensators for dealing with specific LCD birefringence problems have been disclosed. For instance, a negative birefringence film whose optic axis is normal to the film plane is disclosed in Japan Display '92 247-250 for improving the viewing angle of a normally white mode twisted nematic LCD. Also, angular compensation for a normally white mode twisted nematic or super twisted nematic LCD using a short pitch cholesteric liquid crystal polymer film such that the intra-plane refractive index is substantially averaged and larger than the refractive index in the thickness direction is disclosed in EP 0 531 120. The compensation film essentially has a negative uniaxial structure whose optic axis is normal to the plane of the film. Multilayer films and holographically formed grating structures have also been used as negative birefringence compensators for normally white mode twisted nematic LCDs. SID '95, P47, 555-558, S.T. Wu discloses the use of biaxial compensators to improve the contrast ratio both on-axis and off-axis.

SID '95, P50 Nishimura "Colour compensation" discloses the use of a liquid crystal polymer film with a super twisted nematic structure and controllable retardation, twist angle and dispersion for improving the contrast ratio of super twisted nematic LCDs over the visible spectrum at normal incidence.

According to a first aspect of the invention, there is provided a broadband cholesteric optical device comprising a broadband cholesteric layer, characterised by a first compensator for providing a desired off-axis device performance, the first compensator comprising a first layer having positive birefringence and an optic axis substantially perpendicular to the first layer.

The first compensator may comprise a second layer having negative birefringence and an optic axis substantially perpendicular to the second layer.

The desired off-axis device performance may be reduced angular dependence.

The cholesteric layer may have a graded pitch which increases monotonically from a first surface to a second surface thereof.

The cholesteric layer may have a graded refractive index which increases monotonically from a first surface to a second surface thereof.

The sum of the off-axis birefringence of the first and second layers may be substantially equal to zero for a wavelength corresponding to the shortest pitch of the cholesteric layer and substantially equal to but opposite that of the

cholesteric layer for a wavelength corresponding to the longest pitch of the cholesteric layer, and the first compensator may be disposed adjacent the first surface of the cholesteric layer.

The refractive index dispersions of the first and second layers may be such that:

$$|\Delta n_1\ (400)\ /\Delta n_1\ (700)\ -\Delta n_2\ (400)\ /\Delta n_2\ (700)| > 0$$

where $\Delta n_1(400)$ and $\Delta n_1(700)$ are the birefringences of the first layer at wavelengths of 400 and 700 nanometres respectively, and $\Delta n_2(400)$ and $\Delta n_2(700)$ are the birefringences of the second layer at wavelengths of 400 and 700 nanometres, respectively; i.e. Δn is the magnitude of the difference between the refractive indices in the plane and perpendicular to the plane.

The sum of the off-axis birefringence of the first and second layers may be substantially equal to zero for a wavelength corresponding to the longest pitch of the cholesteric layer and substantially equal to but opposite that of the cholesteric layer for a wavelength corresponding to the shortest pitch of the cholesteric layer, and the first compensator may be disposed adjacent the second surface of the cholesteric layer.

The refractive index dispersions of the first and second layers may be such that:

$$|\Delta n_2\ (400)\ /\Delta n_2\ (700)\ -\ \Delta n_1\ (400)\ /\Delta n_1\ (700)| > 0$$

where $\Delta n_1(400)$ and $\Delta n_1(700)$ are the birefringences of the first layer at wavelengths of 400 and 700 nanometres, respectively, and $\Delta n_2\ (400)$ and $\Delta n_2(700)$ are the birefringences of the second layer at wavelengths of 400 and 700 nanometres, respectively.

The first layer may comprise a reactive mesogenic material. The first layer may comprise a homeotropically aligned reactive mesogenic material.

The first layer may comprise a reactive mesogenic material. The first layer may comprise a homeotropically aligned reactive mesogenic material.

The first layer may comprise part of the cholesteric layer having a predetermined alignment.

The first layer may comprise at least one stretched polymer film.

The first layer may comprise a plurality of uniaxial films, each of which has negative birefringence and an optic axis substantially in the plane thereof, the optic axes of the or each adjacent pair of the uniaxial films being angularly spaced by a non-zero angle. The first layer may comprise two uniaxial films whose optic axes are substantially perpendicular to each other.

The first layer may comprise a plurality of biaxial films, each of which has a refractive index in a direction perpendicular to the film which is greater than the average of the refractive indices in the plane of the film, the optic axes corresponding to the smaller of the in-plane refractive indices of the or each adjacent pair of films being angularly spaced by a non-zero angle. The first layer may comprise two biaxial films whose optic axes corresponding to the smaller of the in-plane refractive indices are substantially perpendicular to each other.

The second layer may comprise a cholesteric layer having a pitch corresponding to a wavelength of less than substantially 440 nanometres. The second layer may comprise part of the cholesteric layer.

The second layer may comprise a cast polymer film. The polymer may be a polyimide.

The second layer may comprise a discotic liquid crystal material.

The second layer may comprise at least one stretched polymer film.

The second layer may comprise a plurality of films, each of which comprises a uniaxial material having an optic axis in the plane thereof, the optic axes of the or each adjacent pair of films being angularly spaced by a non-zero angle. The second layer may comprise two films and the optic axes may be substantially perpendicular to each other.

The second layer may comprise a plurality of biaxial films, each of which has a refractive index in a direction perpendicular to the film which is less than the average of the refractive indices in the plane of the film, the optic axes corresponding to the greater of the in-plane refractive indices of the or each adjacent pair of films being angularly spaced by a non-zero angle The second layer may comprise two biaxial films whose optic axes corresponding to the greater of the in-plane refractive indices are substantially perpendicular to each other.

The first compensator may include an on-axis retarder. The retarder may be a quarter waveplate.

The cholesteric layer may be disposed between the first compensator and a second compensator, which comprises a plurality of layers, a first of which has positive birefringence and an optic axis substantially perpendicular to the first layer and a second of which has negative birefringence and an optic axis substantially perpendicular to the second layer. The second layer may include an on-axis retarder. The retarder may be a quarter waveplate.

According to a second aspect of the invention, there is provided a polariser characterised by comprising a device according to the first aspect of the invention.

According to a third aspect of the invention, there is provided a filter characterised by comprising a device according to the first aspect of the invention.

According to a fourth aspect of the invention, there is provided a liquid crystal device characterised by including a device according to the first aspect of the invention.

According to a fifth aspect of the invention, there is provided a polarising beam-splitter characterised by comprising a device according to the first aspect of the invention.

It is thus possible to provide a device which makes use of dispersion to vary the amount of off-axis birefringence with wavelength so as to reduce or compensate for wavelength-dependent off-axis birefringence of a broadband cholesteric layer. For instance, the intensity and polarisation of transmitted and reflected light from a cholesteric layer may be controlled as a function of wavelength, polarisation and angle of incidence of illuminating light. Further on-axis retarding layers may be included to and/or the angle of emergence of the optical performance of the device may be substantially reduced. It is therefore possible to provide devices such as polarisers and spectral filters of improved performance over a relatively large range of angles of incidence and/or emergence.

The invention will be further described, by way of example, with reference to the accompanying drawings in which:

Figures 1a to 1c are graphs of transmission in percent against wavelength in nanometres of a known broadband cholesteric polariser for different angles of incidence;

Figures 2a to 2c are graphs similar to Figures 1a to 1c, respectively, showing the performance for light passing in the opposite direction;

Figures 3a to 3c are graphs similar to Figures 1a to 1c, respectively, illustrating simulated performance of a known type of cholesteric device;

Figures 4a to 4c are similar to Figures 2a to 2c, respectively, illustrating simulated performance of a known type of cholesteric device;

Figure 5a is a diagrammatic representation of a known single layer cholesteric reflector;

Figure 5b illustrates diagrammatically a simplified structure of part of the layer of Figure 5a;

Figures 6a to 6d are graphs of transmission against wavelength in nanometres illustrating simulated performance of a device of the type shown in Figure 5a for different angles of incidence;

Figures 7a to 7d are similar to Figures 6a to 6d, respectively, for a device comprising a thin reflecting layer;

Figure 8a to 8d are similar to Figures 6a to 6d, respectively, illustrating the simulated performance of a thick reflecting layer;

Figures 9a to 9d are similar to Figures 7a to 7d, respectively, illustrating the simulated performance of a thick reflecting layer covered by a thick infrared (IR) layer;

Figure 10 is a diagram illustrating the structure of an optical device constituting a first embodiment of the invention;

Figures 11a to 11d are graphs of transmission against wavelength in nanometres illustrating the simulated performance of the device of Figure 10 for different angles of incidence;

Figures 12a to 12d are similar to Figures 11a to 11d, respectively, for a device of the type shown in Figure 10 from which a compensator has been omitted;

Figures 13a to 13d are similar to Figures 11a to 11d, respectively, for light passing in the opposite direction through the device;

Figures 14a to 14d are similar to Figures 12a to 12d, respectively, for light passing in the opposite direction;

Figure 15 is a diagram showing an optical device constituting a second embodiment of the invention;

Figure 16 illustrates diagrammatically a backlight arrangement for an LCD constituting a third embodiment of the

invention;

Figure 17 is a diagram illustrating the structure of an optical device constituting a fourth embodiment of the invention;

Figures 18a to 18d are similar to Figures 11a to 11d, respectively, for the optical device of Figure 17;

Figures 19 and 20 are diagrams illustrating two applications of the device shown in Figure 15;

Figures 21 and 22 are diagrams showing optical devices constituting fifth and sixth embodiments of the invention;

Figure 23 is a diagram showing an optical device constituting a seventh embodiment of the invention;

Figures 24 and 25 are perspective diagrams showing optical devices constituting eighth and ninth embodiments of the invention;

Figure 26 is a diagram showing an optical device constituting a tenth embodiment of the invention;

Figures 27 and 28 are perspective diagrams showing optical devices constituting eleventh and twelfth embodiments of the invention; and

Figures 29 and 30 illustrate diagrammatically backlight arrangements for LCDs constituting fourteenth and fifteenth embodiments of the invention.

Like reference numerals refer to like parts throughout the drawings.

Figure 1a of the accompanying drawings is a graph of transmittance in percent against wavelength in nanometres illustrating the performance of a known polariser. The polariser comprises a broadband left-handed monotonically graded pitch cholesteric film illuminated on its shorter pitch surface by white light with an angle of incidence of zero degrees. The unbroken line illustrates the transmittance of right handed circularly polarised light whereas the broken line illustrates the transmittance of left-handed circularly polarised light. In order to act as an achromatic broadband polariser, the ideal performance would be for the left handed circularly polarised light to be transmitted with a uniform transmittance across the whole of the visible spectrum with minimal insertion loss whereas the right handed circularly polarised light would be uniformly attenuated across the visible spectrum with maximal attenuation. As shown in Figure 1a, the on-axis performance of the known type of polariser approaches the ideal performance and is adequate for many practical applications.

Figure 1b is a graph similar to that of Figure 1a but illustrates the performance for light which is incident on the short pitch surface at 20 degrees. The attenuation performance for right handed circularly polarised light is slightly degraded and the curve for left handed circularly polarised light is showing signs of some degradation of achromatic performance.

Figure 1c illustrates operation for light incident at 40 degrees. The transmittance curves for left handed and right handed circularly polarised light are similar so that the extinction ratio (ratio of transmittance of the desired polarisation to the transmittance of the undesired polarisation) is very poor and, throughout part of the visible spectrum, is negative. Thus, as the angle of incidence increases, the performance of the broadband polariser deteriorates until, at angles of incidence of the order of 40 degrees, the polariser ceases to act as a polariser at all.

Figures 2a to 2c of the accompanying drawings correspond to Figures 1a to 1c, respectively, but illustrate the performance for light incident at angles of 0, 20 and 40 degrees on the long pitch surface of the broadband polariser. Again, the performance deteriorates with increasing angle of incidence such that the achromaticity of the polariser reduces and the extinction ratio reduces until, for high angles of incidence, the polariser ceases to be effective at all for at least part of the visible spectrum.

Figures 3a to 3c and 4a to 4c correspond to Figures 1a to 1c and 2a to 2c, respectively, but illustrate the results of a simulation using a 4 x 4 transfer matrix optics modelling program. The simulated performance represents a reasonably close approximation to the performance actually obtained and assists in understanding the mechanisms involved in degrading the optical performance of the broadband polariser.

The response may be understood in terms of the off-axis birefringence of the thick cholesteric layer which is optically in front of the layers of cholesteric material at some distance from the illuminated surface of the polariser. For example, the region of the broadband polariser which reflects circularly polarised light at a wavelength of 550 nanometres is separated from the light source by a thick layer of cholesteric liquid crystal polymer (CLCP) which alters the polarisation state of the off-axis incident polarised light. This is illustrated in Figure 5a, which shows the polariser 1 having a short

pitch surface 2 and a long pitch surface 3. An intermediate layer 4 is responsible for reflection at 550 nanometres but the portion of the polariser between the layer 4 and the surface 2 alters the polarisation state of the off-axis incident light.

The effect of this thick intermediate layer 5, which has a smaller pitch than that of the layer 4 for reflecting light at 550 nanometres at normal incidence, may be considered by approximating the layer 5 of varying pitch by means of a layer of constant pitch which is much smaller than the pitch of the layer 4. In this case, the chiral nature of the thick layer 5 is not "visible" to incident light of 550 nanometre wavelength. To a first approximation, such light sees the "averaged structure" illustrated in Figure 5b. The layer 5 is thus simulated as a layer whose pitch corresponds to UV wavelengths.

Figures 6a to 6d are graphs of transmission against wavelength for light incident on the simulated structure comprising the UV layer and the layer 4 at angles of incidence of zero, 15.3, 31.3 and 49.5 degrees, respectively. Figures 7a to 7d correspond to Figures 6a to 6d, respectively, but for a simulation in which the UV layer is omitted. These results illustrate that, off-axis, the polarisation state of the incident light is substantially affected by the thick UV layer such that right handed circularly polarised light is partially converted to left handed circularly polarised light, which is not reflected by the layer 4 reflecting at 550 nanometres. Further, the left handed circularly polarised light is partially converted to right handed circularly polarised light which is reflected by the layer 4. Thus, the averaged structure illustrated in Figure 5b has a performance which is consistent with the effects of off-axis birefringence and this is believed to be the mechanism which causes the off-axis deterioration in performance.

Figures 8a to 8d correspond to Figures 7a to 7d, respectively, but illustrate the simulated result where the thin CLCP layer 4 reflecting at 550 nanometres wavelength is covered by a thick CLCP of the same pitch and thus reflecting at the same wavelength as the layer 4. Averaging of the chiral structure does not take place and, for the parameters and angles illustrated, there is negligible difference between the off-axis behaviour of the thin and thick "green" layers as may be seen by comparing Figures 7a to 7d with Figures 8a to 8d, respectively.

Figures 9a to 9d correspond to Figures 7a to 7d but illustrate the effect of covering the thin layer 4 with a thick layer which has a larger pitch such that it is reflective to infrared radiation on-axis. The presence of this layer affects performance as illustrated in Figures 9a to 9d. However, as may be seen by comparing Figures 6a to 6d with Figures 9a to 9d, respectively, the effect of the thick layer depends on whether its pitch is greater or less than that of the layer 4 having a pitch capable of reflecting the incident light.

The device shown in Figure 10 constitutes an embodiment of the invention and is a broadband polariser for reflecting circularly polarised light of a first handedness and for transmitting circularly polarised light of a second handedness throughout the visible spectrum. The device comprises a broadband cholesteric film 1 having a graded pitch which varies monotonically from a short pitch surface 2 of the film 1 to a long pitch surface 3. The film 1 is, for instance, of the same type as that shown in Figure 5a.

A positive birefringence layer 8 is disposed adjacent or in contact with the short pitch surface 2 of the film 1. The layer 8 is 14.3 micrometres thick and has ordinary and extraordinary refractive indices n4 and n3 such that n4 is less than n3 and the optic axis is substantially perpendicular to the layer 8 and parallel to the axis of the device. For instance, the extraordinary refractive index n3 may have a value of 1.7 at a wavelength of 400 nanometres and 1.55 at a wavelength of 700 nanometres. The ordinary refractive index n4 may have a value of 1.5 at a wavelength of 400 nanometres and 1.36 at a wavelength of 700 nanometres.

The positive birefringence layer 8 is disposed between the broadband cholesteric film 1 and a negative birefringence layer 9 which is 11 micrometres thick.

The optic axis of the layer 9 is substantially perpendicular to the layer and parallel to the optical axis of the device. The layer 9 has an ordinary refractive index n2 of 1.70 at a wavelength of 400 nanometres and 1.55 at a wavelength of 700 nanometres. The layer 9 has an extraordinary refractive index n1 of 1.5 at 400 nanometres and 1.41 at 700 nanometres. The layers 8 and 9 are uniaxial.

The phase retardation of the films 8 and 9 at oblique incident angles is given by:

$$\delta(\theta,\lambda) = 2\pi d\Delta n/\lambda\cos\theta \quad (1)$$

where θ is the incident angle of light in the LC medium, λ is the wavelength, d is the film thickness and Δn is given by:

$$\Delta n_{(1,2)} = n_1 n_2 (n_1^2\cos^2\theta + n_2^2\sin^2\theta)^{-1/2} - n_2 \quad (2)$$

for the layer 9 and

$$\Delta n_{(3,4)} = n_3 n_4 (n_3^2 \cos^2\theta + n_4^2 \sin^2\theta)^{-1/2} - n_4 \quad (3)$$

for the layer 8 of the double layer compensator.

The total phase retardation of the two layers 8, 9 is given by the sum of the phase retardations of the two films:

$$\delta(\theta,\lambda)_{1,2} + \delta(\theta,\lambda)_{3,4} = 2\pi(d_{12}\Delta n_{(1,2)} + d_{34}\Delta n_{(3,4)}/\lambda\cos\theta \quad (4)$$

This phase retardation depends on wavelength both due to the explicit λ term in equation (4) as well as the dispersion of the refractive indices n_1, n_2, n_3, and n_4.

The dispersions and thicknesses of the layers 8, 9 are arranged such that the amount of off-axis phase retardation, or off-axis birefringence, varies with wavelength so as to counteract the depth-dependence of the off-axis birefringence of the graded-pitch cholesteric film 1. Provided that the pitch of the cholesteric film varies monotonically from one face to the other, improved angular response can be achieved with a simple double-layer compensator of the form shown in Figure 10. Compensation can be achieved also by placing the negative birefringence layer 9 closer to the cholesteric layer 1 than the positive birefringence layer 8.

Where the compensator is next to the short pitch surface 2, the dispersion of the materials of the layers 8 and 9 and should be such that:

$$(\Delta n_9(400)/\Delta n_9(700)) - (\Delta n_8(400)/\Delta n_8(700)) > 0$$

where Δn is the magnitude of the difference between the refractive indices in the plane and perpendicular to the plane, $\Delta n_9(400)$ and $\Delta n_9(700)$ are the differences for the layer 9 at wavelengths of 400 and 700 nanometres, respectively, and $\Delta n_8(400)$ and $\Delta n_8(700)$ are the differences for the layer 8 at wavelengths of 400 and 700 nanometres, respectively.

Polarised light propagating through a slab of cholesteric material of longer pitch than the wavelength of light experiences significant circular birefringence in addition to linear birefringence. This is not removed by the present arrangement. Consequently, it is preferred to have the compensation next to the short pitch surface 2 of the cholesteric film if compensation at only one side of the device is required. In the case where the compensator is next to the long pitch surface 3 (as described hereinafter), reasonable compensation may be achieved if the dispersion of the materials of the layers 8 and 9 are such that:

$$(\Delta n_8(400)/\Delta n_8(700)) - (\Delta n_9(400)/\Delta n_9(700)) > 0$$

For the device shown in Figure 10, at the wavelength corresponding to the shortest pitch of the cholesteric film 1, no off-axis birefringence is required and the off-axis retardance of the two layers of the compensator substantially cancel. In particular, because the retardations of the layers 8 and 9 are of opposite sign, it is possible to choose the relative thickness of the layers 8 and 9 so that, at a wavelength corresponding to the shortest pitch of the cholesteric film 1, the retardations of the layers 8 and 9 substantially cancel each other over a wide range of angles.

Conversely, at the wavelength corresponding to the longest pitch of the cholesteric film 1, off-axis birefringence of equal magnitude but opposite sign to the off-axis birefringence of the cholesteric film 1 at that wavelength is required. The dispersion of the negative birefringence layer 9 is greater than the dispersion of the positive birefringence layer 8. In other words, the birefringence of the negative birefringence layer 9 decreases at a faster rate with increasing wavelength than for the positive birefringence layer 8. For wavelengths corresponding to the longest pitch of the cholesteric film 1, the combination of the positive and negative birefringence films 8 and 9 can be approximated as a positive birefringence structure and the cholesteric film 1 can be approximated as a negative birefringence structure. The overall thickness of the layers 8 and 9 is then chosen so as to roughly cancel the effects of the negative birefringence of the cholesteric film 1.

For more complex pitch variations, a compensator comprising more than two layers may be required. Also, the compensator may be placed before and/or after the cholesteric film 1 to provide greater control of the angular behaviour. The correct location of the or each compensator depends on the application.

Figures 11a to 11d are graphs illustrating the performance of the device shown in Figure 10 obtained by simulation. The unbroken curve illustrates the transmission of right handed circularly polarised light whereas the broken line curve illustrates the transmission of left handed circularly polarised light. Figure 11a illustrates the on-axis performance i.e. for light incident at zero degrees, whereas Figure 11b, 11c and 11d illustrate performance for light incident at 15, 31

and 49 degrees, respectively. As shown in each of these drawings, transmission of left handed circularly polarised light is high and varies little throughout the visible spectrum, even in the case of light incident at 49 degrees as shown in Figure 11d. Also, attenuation of right handed circularly polarised light remains high throughout the visible spectrum and with substantially achromatic performance. The device therefore operates as a highly achromatic broadband polariser and maintains a good extinction ratio throughout the visible spectrum and for large angles of incidence.

Figures 12a to 12d correspond to Figures 11a to 11d, respectively, but illustrate operation of the device shown in Figure 10 with the compensator comprising the layers 8 and 9 removed. As shown in Figures 12a and 12b, the on-axis performance and performance for light which is incident at 15 degrees on the short pitch surface 2 is similar to the performance with the compensator as illustrated in Figures 11a and 11b. However, the performance deteriorates for larger angles of incidence as shown in Figures 12c and 12d. For a 31 degree angle of incidence, the device still functions as a polariser but the extinction ratio is seriously reduced for longer wavelength light and is no longer approximately achromatic. At a 49 degree angle of incidence, the performance has deteriorated to the point where the device is actually more transmissive to the undesired polarisation state than to the desired polarisation state. Thus, the presence of the compensator greatly increases the off-axis performance.

Figure 13a to 13d are graphs similar to Figure 11a to 11d, respectively, but illustrate the performance of an alternative embodiment. The cholesteric film 1 is oriented such that light is incident toward the long pitch surface 3. The positive birefringence layer 8 and the negative birefringence layer 9 are disposed between the light source and the film 1 but differ from the layers described hereinbefore in that the positive birefringence film 8 has a thickness of 19.8 micrometres, an ordinary refractive index n4 of 1.56 at a wavelength of 400 nanometres, and 1.50 at a wavelength of 700 nanometres and an extraordinary refractive index n3 of 1.80 at 400 nanometres and 1.70 at 700 nanometres whereas the film 9 has a thickness of 15 micrometres, an ordinary refractive index n2 of 1.75 at 400 nanometres and 1.72 at 700 nanometres, and an extraordinary refractive index n1 of 1.56 at 400 nanometres and 1.51 at 700 nanometres. The simulated on-axis performance and performance for light incident at 15 degrees is shown in Figures 13a and 13b and illustrates good achromatic performance and extinction ratio throughout the visible spectrum. Although the performance deteriorates for angles of incidence of 31 and 49 degrees as shown in Figures 13c and 13d, the performance represents a substantial improvement over known devices and, in particular, the film 1 with the compensator comprising the layers 8 and 9 removed, as shown in Figures 14a to 14d. The performance on-axis and for a 15 degree angle of incidence is similar to the performance with the compensator but performance for higher angles of incidence deteriorates substantially as shown in Figures 14c and 14d.

There are a number of techniques and suitable materials for creation of the double-layer compensator. For example, the negative birefringence layer 9 may be fabricated from short pitch cholesteric material. This layer 9 may be incorporated with the broadband cholesteric polarising film 1 or may be separate. Alternatively, a suitably fabricated polyimide film may be used as disclosed in S.T. Wu, P-47, SID '95. The negative birefringence layer 9 may be fabricated from a suitable discotic LC material as disclosed in US 5 518 783. A further alternative may be a biaxially stretched polymer film with little anisotropy in the plane. Furthermore, an effective negative birefringence layer may be fabricated from a two (or more) film stack of positive uniaxial or biaxial materials. Suitable materials may be nematic LC polymers which have planar alignment or stretched polymer films of materials exhibiting positive birefringence (i.e. an increased refractive index along the direction of stretching). The most suitable materials depend upon whether the compensator is next to the short pitch surface 2 or the long pitch surface 3. If the compensator is next to the short pitch surface 2, a high dispersion material is preferable. Suitable high dispersion materials may include biaxially oriented polyethylene naphtalate (Goodfellows, Cambridge, UK) with $\Delta n_{400}/\Delta n_{700} \sim 1.45$ or spin-coatable polyimides eg Ultradel PI-7505, (Amoco Chemical Company, Naperville, USA) $\Delta n_{400}/\Delta n_{700} \sim 1.3$. For the compensator next to the long pitch surface 3, suitable low dispersion materials may include VAC compensation film (Sumitomo Chemical Co., Japan) $\Delta n_{400}/\Delta n_{700} \sim 1.02$ or stacked films of stretched PVA (eg Polatechno, Japan) $\Delta n_{400}/\Delta n_{700} \sim 1.03$.

The positive birefringence layer 8 may be fabricated conveniently from a cured homeotropically aligned liquid crystal or liquid crystal polymer material, for instance as disclosed in EP 524 028. Also it may be possible to orient appropriately a cholesteric liquid crystal or liquid crystal polymer by use of surface effects or application of an electric or magnetic field to create the positive birefringence layer 8. In such a case, this layer may be essentially part of the cholesteric film 1. Additionally the positive birefringence layer may be fabricated from a biaxially stretched polymer film, stretched so that there is very little anisotropy in the plane. Such a film may be fabricated from a material exhibiting negative birefringence when stretched, i.e. exhibiting a decreased refractive index in the direction of stretching. Polymer materials exhibiting this property include polystyrene, poly methyl methacrylate (PMMA), ethylene methacrylate, and acrylonitrile polymers and co-polymers including stryrene acrylonitrile (SAN).

Furthermore, an effective positive birefringence layer may be fabricated from a two (or more) film stack of negative uniaxial or biaxial materials. For negative uniaxial materials, the optic axes are in the film plane but at an angle (90° for two films) to each other. For biaxial materials, the refractive index perpendicular to the plane is larger than the average of the refractive indices in the plane. The optic axes corresponding to the smallest in-plane refractive indices are at an angle (90° for two films) to each other. The films constituting the positiv birefringence layer have similar

optical dispersion properties.

For the compensator next to the short pitch surface 2, a low dispersion positive birefringence layer is required. A suitable material may be biaxially oriented polystyrene film eg OPS (Mitsubishi Chemical Co., Tokyo, japan) $\Delta n_{400}/\Delta n_{700} \sim 1,15$. For the compensator next to the long pitch surface 3 a higher dispersion material is desirable. A suitable material may be a different grade of polystyrene eg AKD biaxially oriented polystyrene (AKD America Investment Corporation, Los Angeles, USA) $\Delta n_{400}/\Delta n_{700} \sim 1.29$ or a high birefringence homeotropically aligned liquid crystal polymer, for example as disclosed in EP 524 028. In general for liquid crystal materials, high birefringence is associated with a high dispersion factor as previously defined.

Although in theory the complete "external" compensator may be fabricated from the cholesteric reflecting film material, this is only convenient or feasible where there is sufficient control of the refractive indices and dispersion.

The final tuning of the off-axis birefringence of the external compensator may be achieved in situ, for example by use of temperature tuning of one of the refractive indices.

In addition, instead of decreasing the angular dependence, the optimum response of the cholesteric film/compensator combination may depend on the application. The compensator may be used to provide matching of the angular response of the cholesteric film to the specific application, such as use with a particular LCD. In such a case, the luminance enhancement achievable by use of a cholesteric film in a recirculating backlight system may be obtained without degrading other features of the system, such as viewing angle or colour balance.

Quarter wave films or other appropriate on-axis retarders may be integrally combined with the off-axis birefringence compensator.

Figure 15 illustrates a device which differs from that shown in Figure 10 in that a further compensator 10 is provided for emergent light leaving the cholesteric film 1. The compensator 10 comprises, for instance, a positive birefringence layer 8' and a negative birefringence layer 9' of the same types as the layers 8 and 9 of the first compensator. Light which is transmitted beyond the layer within the film 1 which reflects left handed circularly polarised light of that wavelength passes through the remainder of the cholesteric film 1 and suffers from the effects of off-axis birefringence. Consequently, light which emerges from the film 1 is not right handed circularly polarised for all wavelengths and at off-axis angles of emergence. The second compensator 10 may be used to counteract these effects so that the light which is transmitted through the whole device is mainly right handed circularly polarised throughout the visible spectrum over a large range of angles of emergence.

Figure 16 illustrates the use of a device comprising a cholesteric polariser 1 and an output compensator 10 in a backlight for an LCD 12. The backlight comprises a light source 14 and reflector 15 which supply light to a light guide 16. Light from the guide 16 is diffused by a diffuser 17 and supplied to the cholesteric polariser 1. Circularly polarised light of one handedness is reflected by the polariser 1 and may be recycled after reversing of its handedness of polarisation. Light of the other handedness of circular polarisation is transmitted by the polariser and the compensator 10 ensures that the output light is substantially of the single handedness of circular polarisation. A broadband quarter wave film 18 converts the circularly polarised light to linearly polarised light with a polarisation vector suitable for application to the LCD 12. The backlight arrangement shown in Figure 16 thus achieves high efficiency of use of the light supplied by the light source 14.

Various modifications may be made within the scope of the invention. For instance, as shown in Figure 17, the negative birefringence layer 9 may be omitted from the device shown in Figure 10 to provide a simpler device whose performance is not as good as that of the device shown in Figure 10 but may be acceptable for some applications. The positive birefringence of the layer 8 may be chosen to offset the negative birefringence experienced, for example, by green light with a wavelength range in the centre of the visible spectrum. The performance of such a simplified device is illustrated in Figures 18a to 18d. The layer 8 has an extraordinary refractive index n3 of 1.7 at 400 nanometres and 1.66 at 700 nanometres. The ordinary refractive index n4 of the layer is 1.65 at 400 nanometres and 1.62 at 700 nanometres.

As shown in Figures 18a to 18c, the performance up to relatively high angles of incidence remains good and represents an improvement over known devices in which no compensator is provided. Even for an angle of incidence of 40 degrees as illustrated in Figure 18d, polarisation separation occurs for wavelengths centred around the middle of the visible spectrum.

The optical devices disclosed herein are suitable for use in applications requiring a polarising beam-splitter for operation throughout a wide range of wavelengths and angles or to operate at high angles to an incident beam, such as of the order of 45 degrees. For instance, Figure 19 illustrates the use of a broadband cholesteric polariser of the type shown in Figure 15 as a polarising beam splitter. Unpolarised light is incident on the filter at an angle of approximately 45 degrees to the plane of the film. If the input compensator 8, 9 were omitted, the polariser would not properly discriminate between left and right handed circularly polarised light at this angle. However, with the input compensator 8, 9, the polariser discriminates well between reflecting left handed circularly polarised light and transmitting right handed circularly polarised light. In the absence of the compensator 10, the polarisation state of the transmitted light would be substantially distorted. However, the compensator 10 ensures that the transmitted light is substantially in the

desired state of circular polarisation.

Such a polarising beam splitter may be used in other applications, such as beam combining or path folding for polarised light. Figure 20 illustrates use of a device of the type shown in Figure 15 for folding an optical system. Again, the input compensator 8, 9 maintains the reflectivity of the polariser across a wide range of wavelengths and angles. The compensator 10 is provided if it is necessary to maintain a high degree of circular polarisation of the transmitted light.

Figure 21 illustrates a device which differs from that shown in Figure 15 in that a quarter waveplate 20 is disposed adjacent the negative birefringence layer 9. Similarly, Figure 22 illustrates a device which differs from that shown in Figure 15 in that a quarter waveplate 20' is disposed adjacent the compensator 10. As is well known, such a quarter waveplate may be used for converting between linearly polarised and circularly polarised light.

Although the quarter waveplates 20 and 20' are shown adjacent the outer surfaces of the negative birefringence layers 9 and 9' respectively, in practice the quarter waveplate may be disposed at any position within the device, for instance between adjacent ones of any of the layers or films including the film 1, or even internally within a layer or film of the compensator 8, 9 or 10.

It is possible for the quarter waveplate to be made integrally with the compensator 8, 9 or with the compensator 10. In particular, the quarter waveplate and one of the layers 8, 9, 8', 9', may be combined in to a single layer. For instance, the quarter waveplate 20 or 20' and the compensator 8, 9 or 10 may be embodied as a first layer or film of a biaxial material whose largest refractive index is perpendicular to the plane and a layer or film of negative uniaxial material whose optic axis is perpendicular to the plane. Another possibility for this combination comprises a layer or film of a biaxial material whose smallest refractive index is perpendicular to the plane and a layer or film of a positive uniaxial material whose optic axis is perpendicular to the plane. Alternatively, if the quarter waveplate is discrete from the compensator 8, 9 or 10, it may be made as a separate film from different materials, such as a multilayer structure, for optimised broad bandwidth.

The device shown in Figure 23 differs from that shown in Figure 10 in that the positive birefringence layer 8 is disposed between and in contact with the long pitch surface 3 of the film 1 and the negative birefringence layer 9. The dispersions of the materials of the layers 8 and 9 are as described hereinbefore for the compensator 8, 9 adjacent the long pitch surface 3.

The device shown in Figure 24 differs from that shown in Figure 10 in that the positive birefringence layer 8 comprises two negative uniaxial films 8a and 8b whose optic axes n_{ea} and n_{eb} are substantially perpendicular to each other. In particular, the films 8a and 8b have extraordinary refractive indices n_{ea} and n_{eb} in the planes of the films 8a and 8b, respectively, and ordinary refractive indices n_{oa} and n_{ob}, respectively, in the orthogonal directions shown in Figure 24. The refractive indices are such that:

$$n_{eb} < n_{ob}$$

$$n_{ea} < n_{oa}$$

The device shown in Figure 25 differs from that shown in Figure 24 in that the films 8a and 8b are biaxial and the smaller in-plane refractive indices n_{2a} and n_{1b} are substantially perpendicular to each other. The films 8a and 8b have refractive indices labelled n_{1a}, n_{2a}, n_{3a}, n_{1b}, n_{2b}, and n_{3b} in orthogonal directions such that:

$$n_{1b} < n_{2b}$$

$$n_{1b} < n_{3b}$$

$$n_{2a} < n_{1a}$$

$$n_{2a} < n_{3a}$$

$$n_{3b} > (n_{1b} + n_{2b})/2$$

$$n_{3a} > (n_{1b} + n_{2b}) / 2$$

The device shown in Figure 26 differs from that shown in Figure 10 in that the positive birefringence layer 8 comprises part of the cholesteric layer 1 having a predetermined alignment.

The device shown in Figure 27 differs from that shown in Figure 10 in that the negative birefringence layer 9 comprises two films 9a and 9b of uniaxial material having optic axes in the planes of the films which are substantially perpendicular to each other. The refractive indices n_{oa}, n_{ea}, n_{ob} and n_{eb} in the directions illustrated in Figure 27 are such that:

$$n_{ea} > n_{oa}$$

$$n_{eb} > n_{ob}$$

The device shown in Figure 28 differs from that shown in Figure 27 in that the films 9a and 9b are biaxial films whose optic axes corresponding to the greater of the in-plane refractive indices are substantially perpendicular to each other. The films 9a and 9b have refractive indices n_{1a}, n_{2a}, n_{3a}, n_{1b}, n_{2b} and n_{3b} in the directions shown such that:

$$n_{3b} < n_{1b}$$

$$n_{3b} < n_{2b}$$

$$n_{3a} < n_{1a}$$

$$n_{3a} < n_{2a}$$

$$n_{3a} < (n_{1a} + n_{2a}) / 2$$

$$n_{3b} < (n_{1b} + n_{2b}) / 2$$

Figure 29 illustrates an LCD and backlight arrangement which differs from that shown in Figure 16 in that the unpolarised light source arrangement 14, 15, 16 is replaced by a polarised light source 14 and a collimating optical element 22. Also, the diffuser 17 is omitted, the compensator 10 is disposed between the collimating optical element 22 and the cholesteric polariser 1, and the broadband quarter wave film 18 is disposed between the polariser 1 and the LCD 12. The compensator 10, the cholesteric polariser 1 and the broadband quarter wave film 18 effectively comprise part of the liquid crystal device and act as an input polariser for the LCD 12.

The arrangement shown in Figure 30 differs from that shown in Figure 29 in that the cholesteric polariser 1 is disposed between the collimating optical element 22 and the compensator 10. Thus, whereas the arrangement shown in Figure 29 has pre-compensation for light entering the polariser 1, the arrangement shown in Figure 30 has post-compensation for light leaving the polariser 1.

Claims

1. A broadband cholesteric optical device comprising a broadband cholesteric layer (1), characterised by a first compensator (8, 9) for providing a desired off-axis device performance, the first compensator (8, 9) comprising a first layer (8) having positive birefringence and an optic axis substantially perpendicular to the first layer (8).

2. A device as claimed in Claim 1, characterised in that the first compensator (8, 9) comprises a second layer (9) having negative birefringence and an optic axis substantially perpendicular to the second layer (9).

3. A device as claimed in Claim 1 or 2, characterised in that the desired off-axis device performance is reduced angular dependence.

4. A device as claimed in any one of the preceding claims, characterised in that the cholesteric layer (1) has a graded pitch which increases monotonically from a first surface (2) to a second surface (3) thereof.

5. A device as claimed in any one of Claims 1 to 3, characterised in that the cholesteric layer (1) has a graded refractive index which increases monotonically from a first surface (2) to a second surface (3) thereof.

6. A device as claimed in Claim 4 when dependent on Claim 2, characterised in that the sum of the off-axis birefringence of the first and second layers (8, 9) is substantially equal to zero for a wavelength corresponding to the shortest pitch of the cholesteric layer (1) and substantially equal to but opposite that of the cholesteric layer (1) for a wavelength corresponding to the longest pitch of the cholesteric layer (1), and in that the first compensator (8, 9) is disposed adjacent the first surface (2) of the cholesteric layer (1).

7. A device as claimed in Claim 6, characterised in that the refractive index dispersions of the first and second (8, 9) layers is such that:

$$|\Delta n_1(400)/\Delta n_1(700)| - |\Delta n_2(400)/(700)| > 0$$

where $\Delta n_1(400)$ and $\Delta n_1(700)$ are the birefringences of the first layer (8) at wavelengths of 400 and 700 nanometres, respectively, and $\Delta n_2(400)$ and $\Delta n_2(700)$ are the birefringences of the second layer (9) at wavelengths of 400 and 700 nanometres, respectively.

8. A device as claimed in Claim 4 when dependent on Claim 2, characterised in that the sum of the off-axis birefringence of the first and second layers (8, 9) is substantially equal to zero for a wavelength corresponding to the longest pitch of the cholesteric layer (1) and substantially equal to but opposite that of the cholesteric layer (1) for a wavelength corresponding to the shortest pitch of the cholesteric layer (1), and in that the first compensator (8) is disposed adjacent the second surface (3) of the cholesteric layer.

9. A device as claimed in Claim 8, characterised in that the refractive index dispersions of the first and second layers (8, 9) is such that:

$$|\Delta n_2(400)/\Delta n_2(700)| - |\Delta n_1(400)/\Delta n_1(700)| > 0$$

where $\Delta n_1(400)$ and $\Delta n_1(700)$ are the birefringences of the first layer (8) at wavelengths of 400 and 700 nanometres, respectively, and $\Delta n_2(400)$ and $\Delta n_2(700)$ are the birefringences of the second layer (9) at wavelengths of 400 and 700 nanometres, respectively.

10. A device as claimed in any one of the preceding claims, characterised in that the first layer (8) comprises a reactive mesogenic material.

11. A device as claimed in Claim 10, characterised in that the first layer (8) comprises a homeotropically aligned reactive mesogenic material.

12. A device as claimed in any one of Claims 1 to 9, characterised in that the first layer (8) comprises part of the cholesteric layer (1) having a predetermined alignment.

13. A device as claimed in any one of Claims 1 to 9, characterised in that the first layer (8) comprises at least one stretched polymer film.

14. A device as claimed in any one of Claims 1 to 10, characterised in that the first layer (8) comprises a plurality of uniaxial films, each of which has negative birefringence and an optic axis substantially in the plane ther of, the optic axes of the or each adjacent pair of the uniaxial films being angularly spaced by a non-zero angle.

15. A device as claimed in Claim 14, characterised in that the first layer (8) comprises two uniaxial films whose optic

axes are substantially perpendicular to each other.

16. A device as claimed in any one of Claims 1 to 10, characterised in that the first layer (8) comprises a plurality of biaxial films, each of which has a refractive index in a direction perpendicular to the film which is greater than the average of the refractive indices in the plane of the film, the optic axes corresponding to the smaller of the in-plane refractive indices of the or each adjacent pair of films being angularly spaced by a non-zero angle.

17. A device as claimed in Claim 16, characterised in that the first layer (8) comprises two biaxial films whose optic axes corresponding to the smaller of the in-plane refractive indices are substantially perpendicular to each other.

18. A device as claimed in Claim 2 or in any one of Claims 3 to 17 when dependent on Claim 2, characterised in that the second layer (9) comprises a cholesteric layer having a pitch corresponding to a wavelength of less than substantially 440 nanometres.

19. A device as claimed in Claim 18, characterised in that the second layer (9) comprises part of the cholesteric layer (1).

20. A device as claimed in Claim 2 or in any one of Claims 3 to 17 when dependent on Claim 2, characterised in that the second layer (9) comprises a cast polymer film.

21. A device as claimed in Claim 20, characterised in that the polymer is a polyimide.

22. A device as claimed in Claim 2 or in any one of Claims 3 to 17 when dependent on Claim 2, characterised in that the second layer (9) comprises a discotic liquid crystal material.

23. A device as claimed in Claim 2 or in any one of Claims 3 to 17 when dependent on Claim 2, characterised in that the second layer (9) comprises at least one stretched polymer film.

24. A device as claimed in Claim 2 or in any one of Claims 3 to 17 when dependent on Claim 2, characterised in that the second layer (9) comprises a plurality of films, each of which comprises a uniaxial material having an optic axis in the plane thereof, the optic axes of the or each adjacent pair of the films being angularly spaced by a non-zero angle.

25. A device as claimed in Claim 24, characterised in that the second layer (9) comprises two films and the optic axes are substantially perpendicular to each other.

26. A device as claimed in Claim 2 or in any one of Claims 3 to 17 when dependent on Claim 2, characterised in that the second layer (9) comprises a plurality of biaxial films, each of which has a refractive index in a direction perpendicular to the film which is less than the average of the refraction indices in the plane of the film, the optic axes corresponding to the greater of the in-plane refractive indices of the or each adjacent pair of films being angularly spaced by a non-zero angle.

27. A device as claimed in Claim 26, characterised in that the second layer (9) comprises two biaxial films whose optic axes corresponding to the greater of the in-plane refractive indices are substantially perpendicular to each other.

28. A device as claimed in any one of the preceding claims, characterised in that the first compensator (8, 9) includes an on-axis retarder (20).

29. A device as claimed in Claim 28, characterised in that the retarder is a quarter waveplate (20).

30. A device as claimed in any one of the preceding claims, characterised in that the cholesteric layer (1) is disposed between the first compensator (8, 9) and a second compensator (10), which comprises a plurality of layers, a first (8') of which has positive birefringence and an optic axis substantially perpendicular to the first layer (8') and a second (9') of which has negative birefringence and an optic axis substantially perpendicular to the second layer (9').

31. A device as claimed in Claim 30, characterised in that the second compensator (10) includes an on-axis retarder (20').

32. A device as claimed in Claim 31, characterised in that the retarder is a quarter waveplate (20').

33. A polariser characterised by comprising a device as claimed in any one of the preceding claims.

34. A filter characterised by comprising a device as claimed in any one of Claims 1 to 32.

35. A liquid crystal device characterised by including a device as claimed in any one of Claims 1 to 32.

36. A polarising beam-splitter characterised by comprising a device as claimed in any one of Claims 1 to 32.

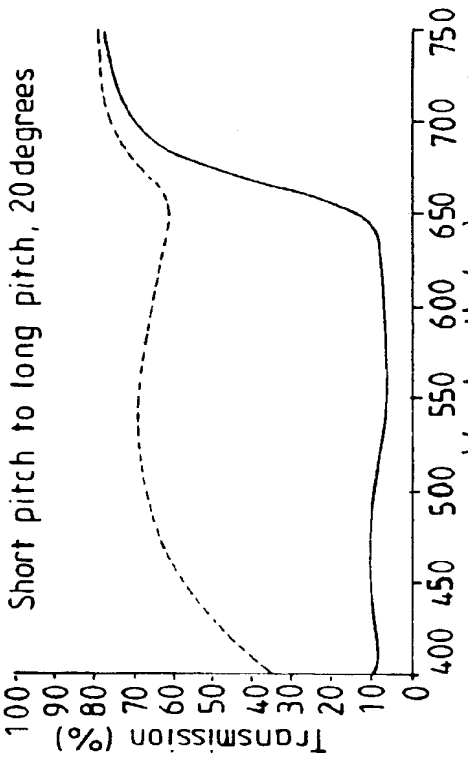


FIG. 1a

FIG. 1b

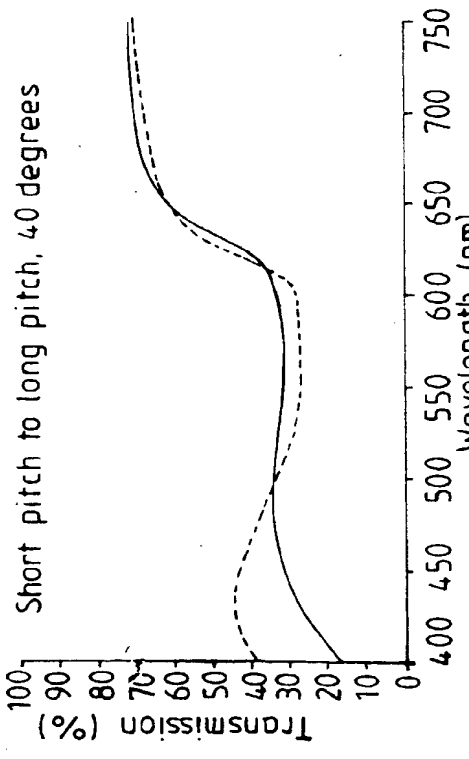


FIG. 1c

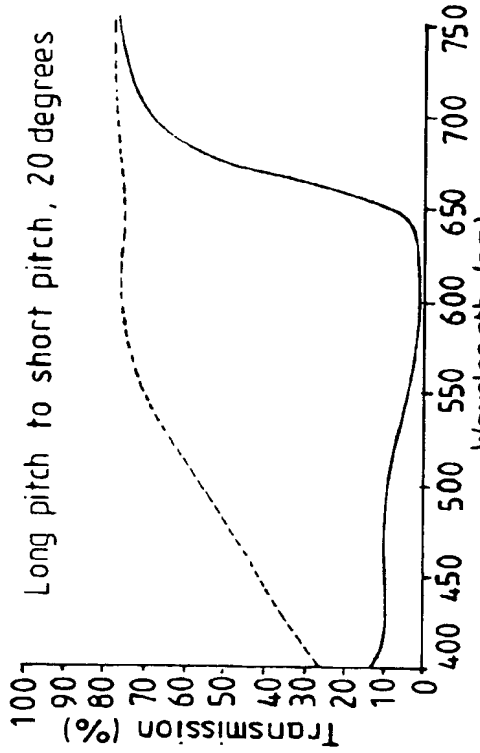


FIG. 2b

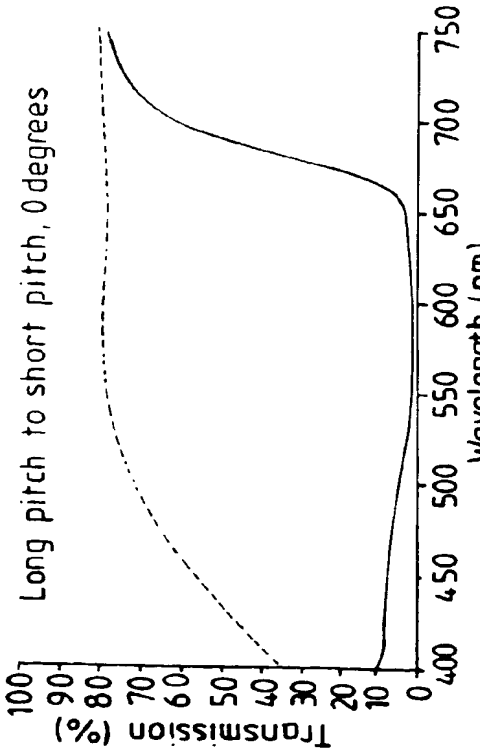


FIG. 2a

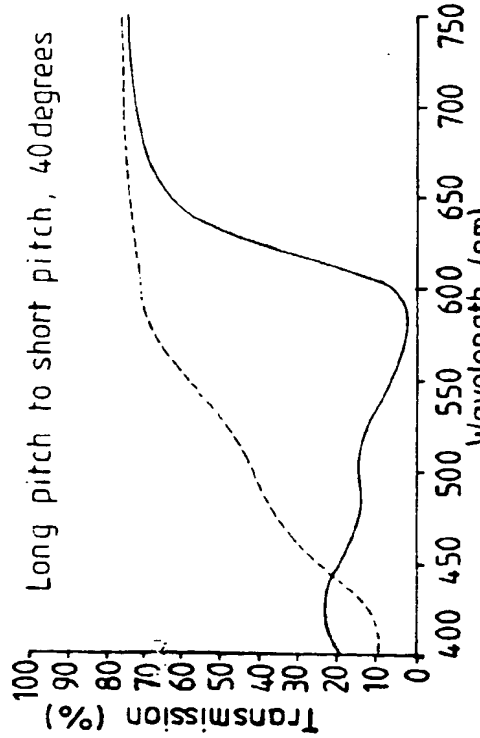


FIG. 2c

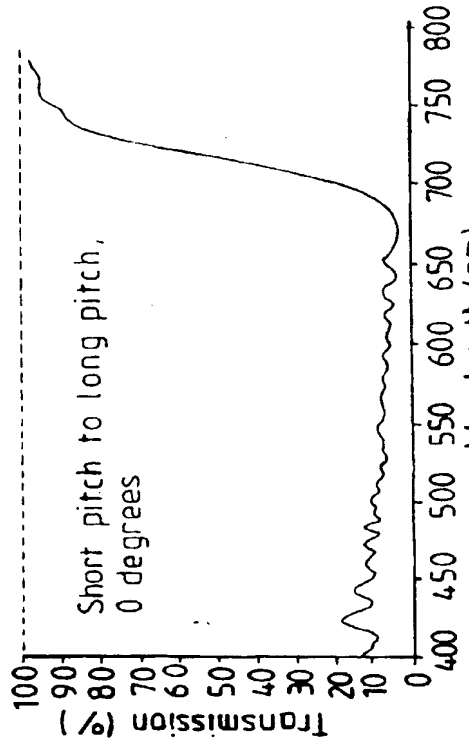


FIG. 3a

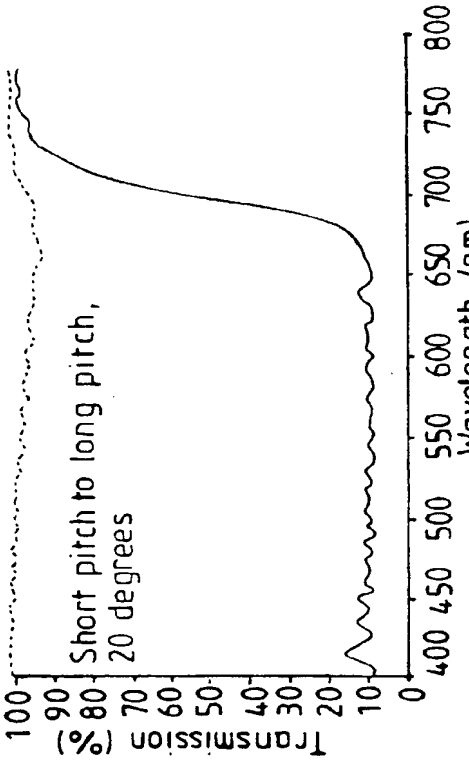


FIG. 3b

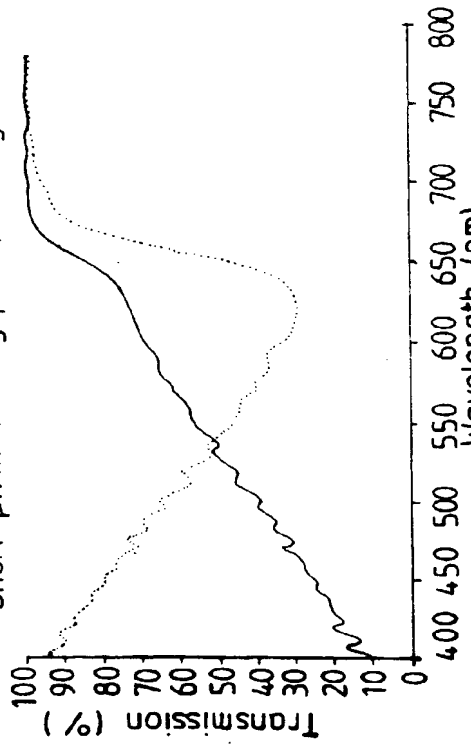


FIG. 3c

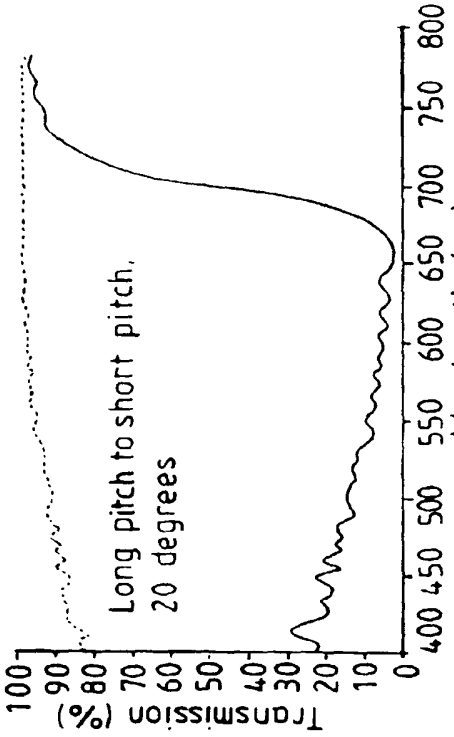


FIG. 4a

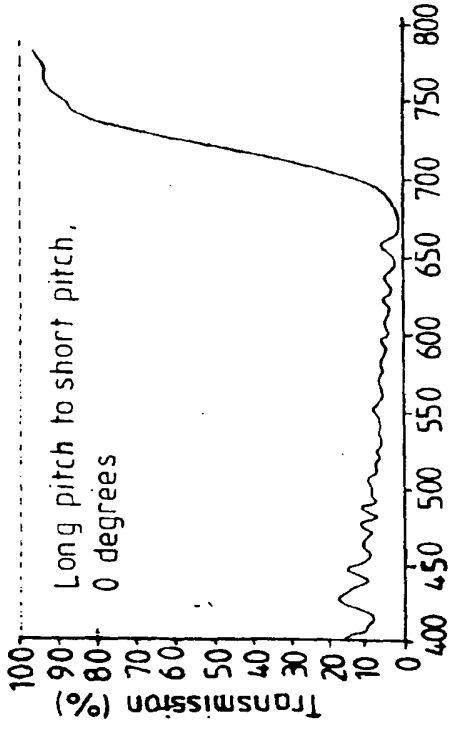


FIG. 4b

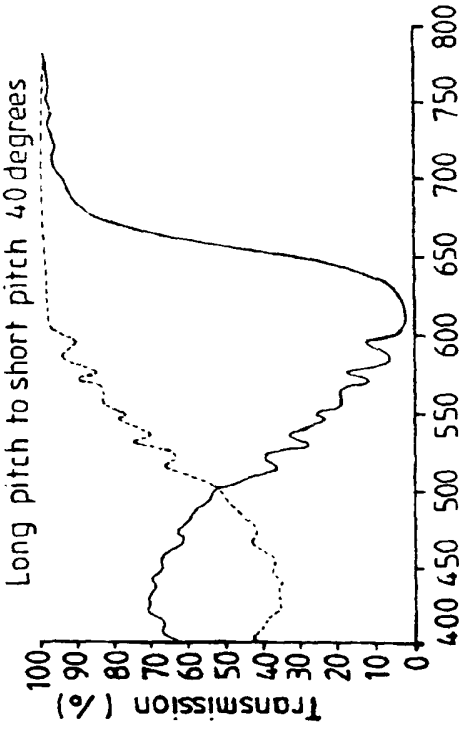


FIG. 4c

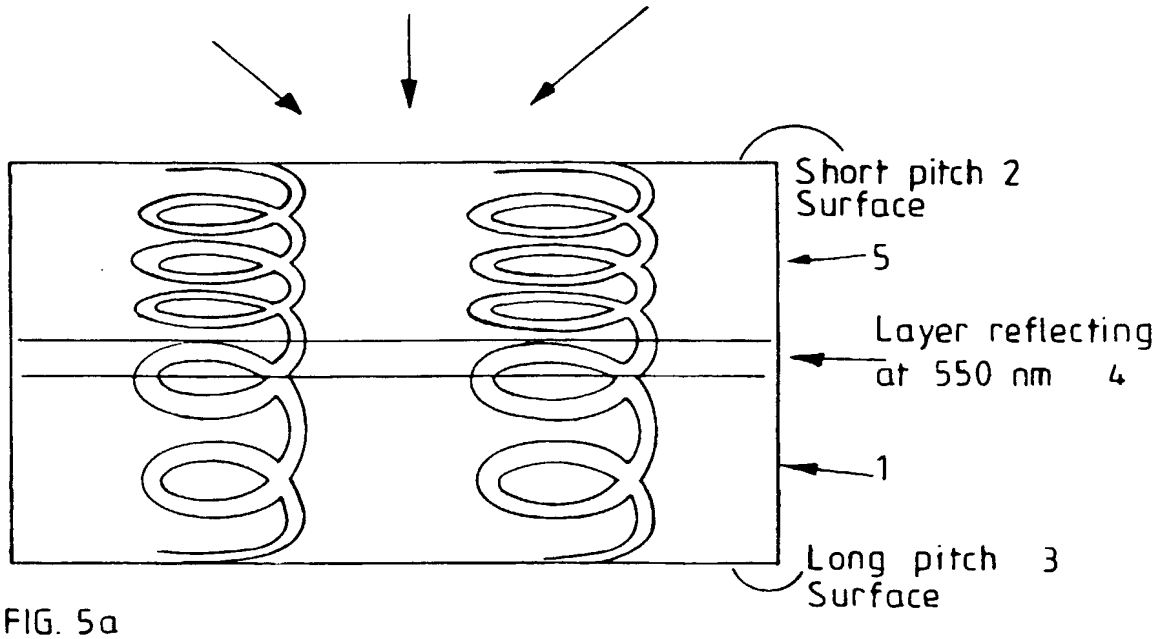
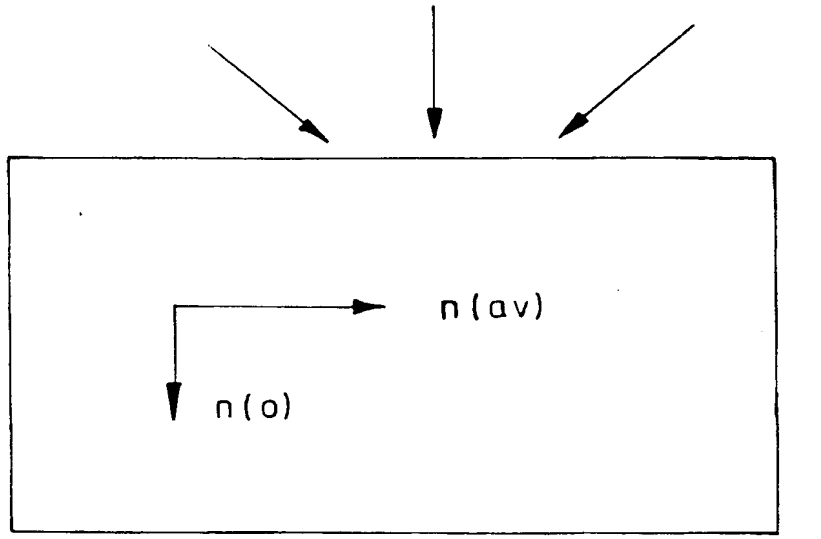


FIG. 5a



$$n(av) \sim \frac{n(e) + n(o)}{2}$$

FIG. 5b

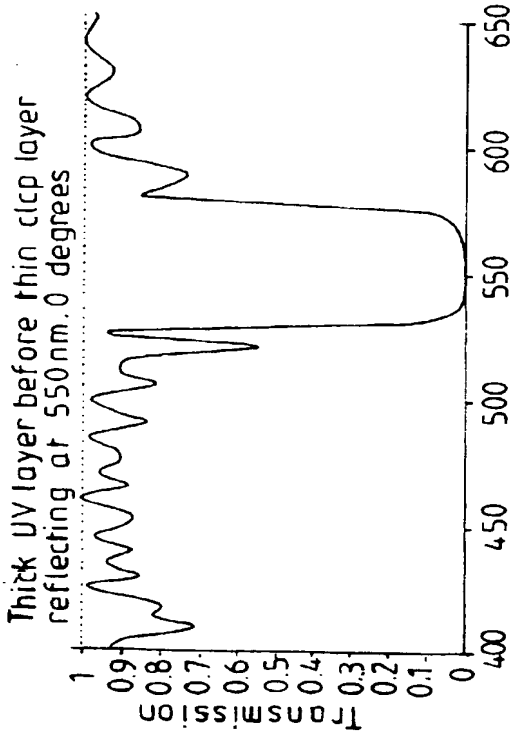


FIG. 6a

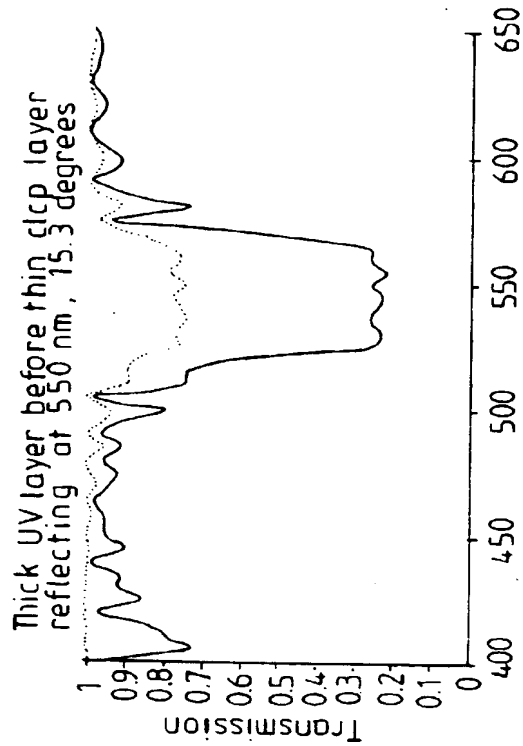


FIG. 6b

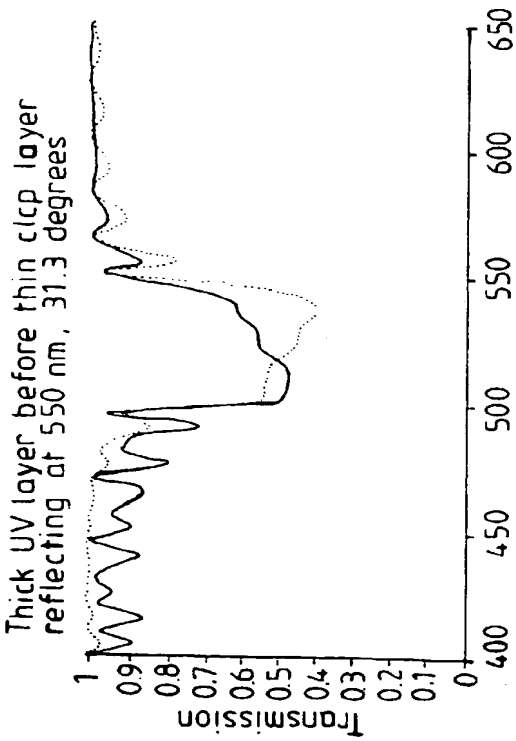


FIG. 6c

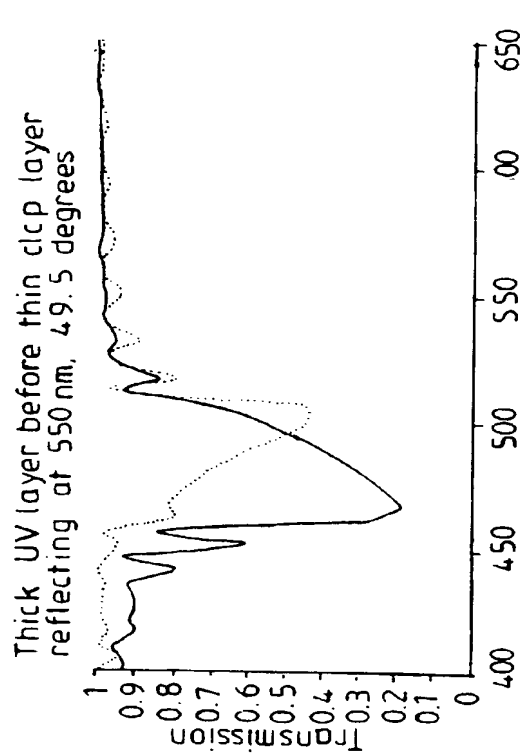


FIG. 6d

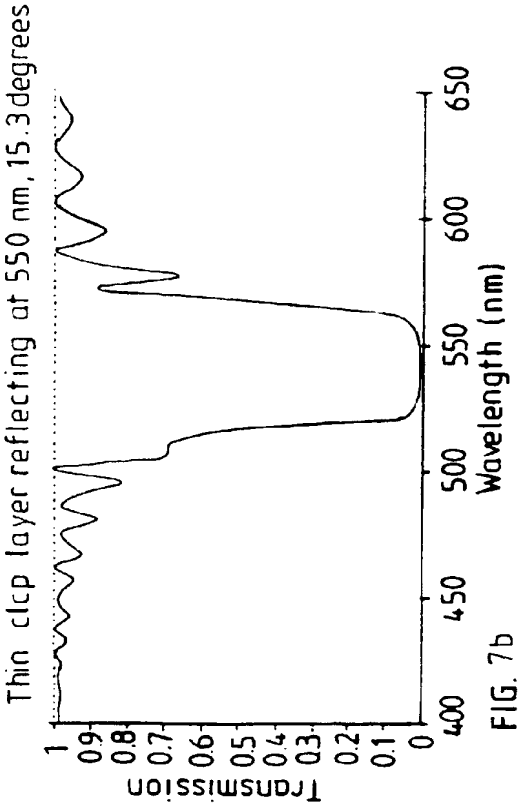


FIG. 7a

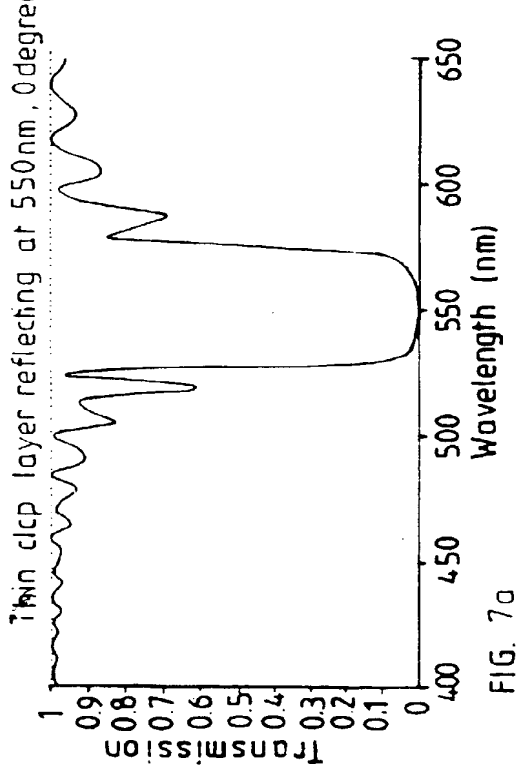


FIG. 7c

FIG. 7b

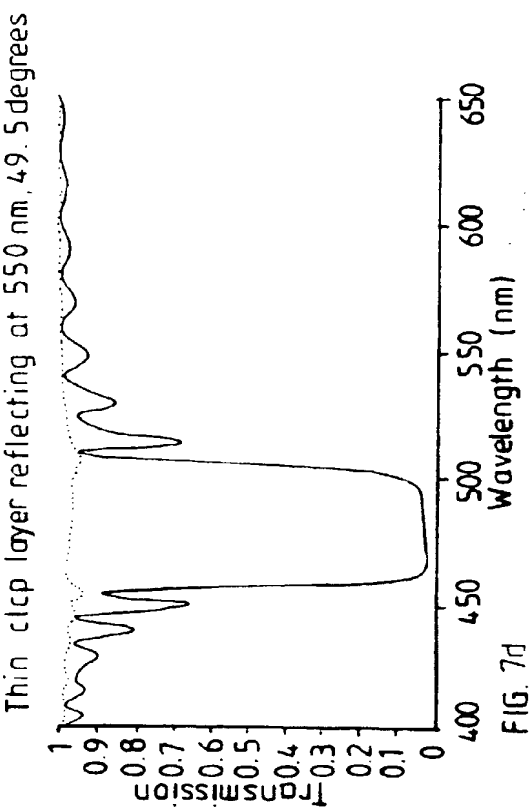


FIG. 7d

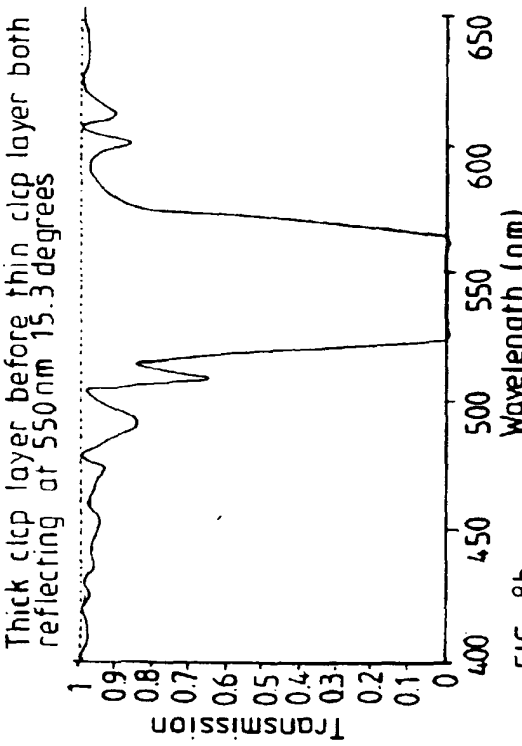


FIG. 8b

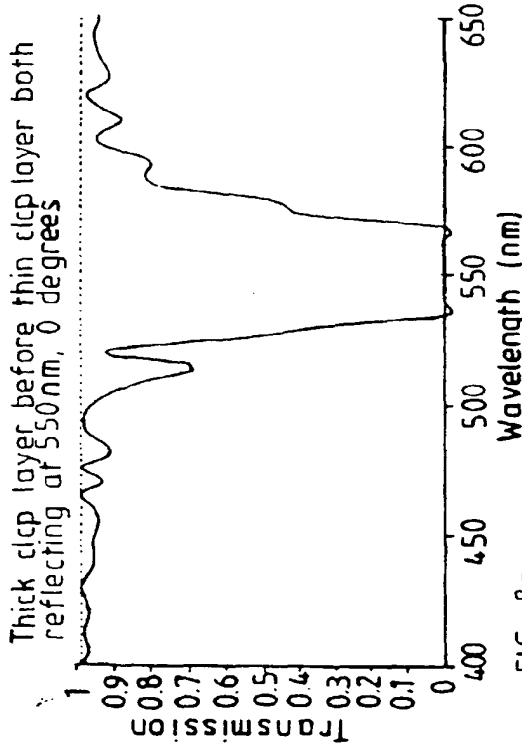


FIG. 8a

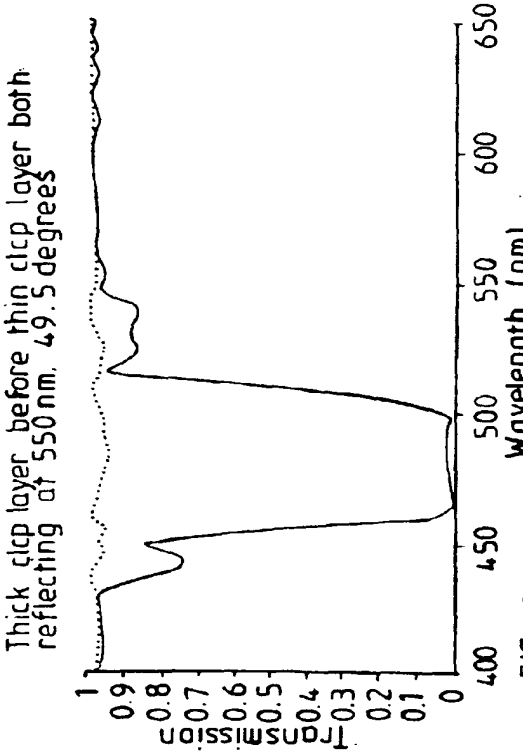


FIG. 8d

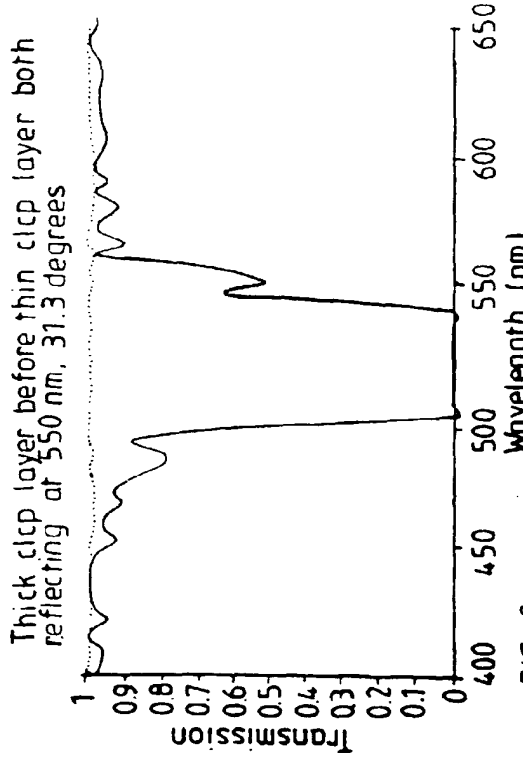


FIG. 8c

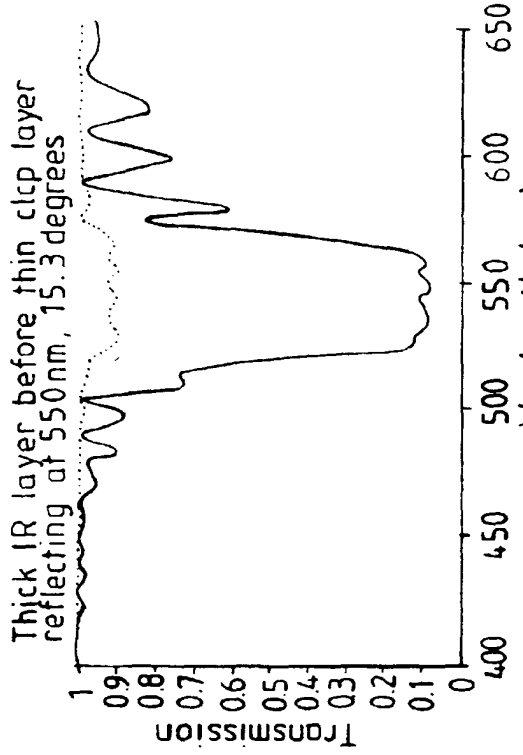


FIG. 9a

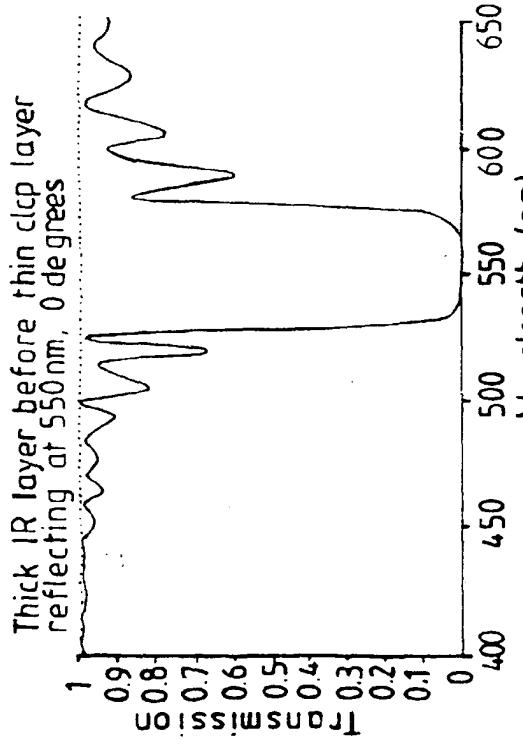


FIG. 9b

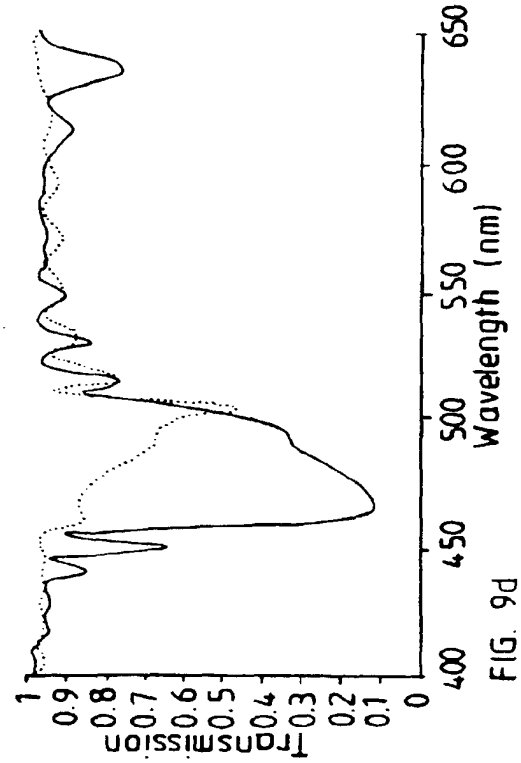


FIG. 9c

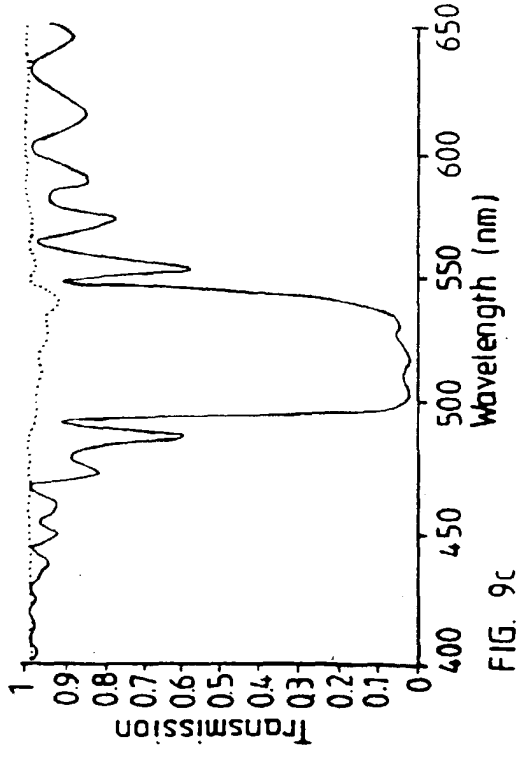


FIG. 9d

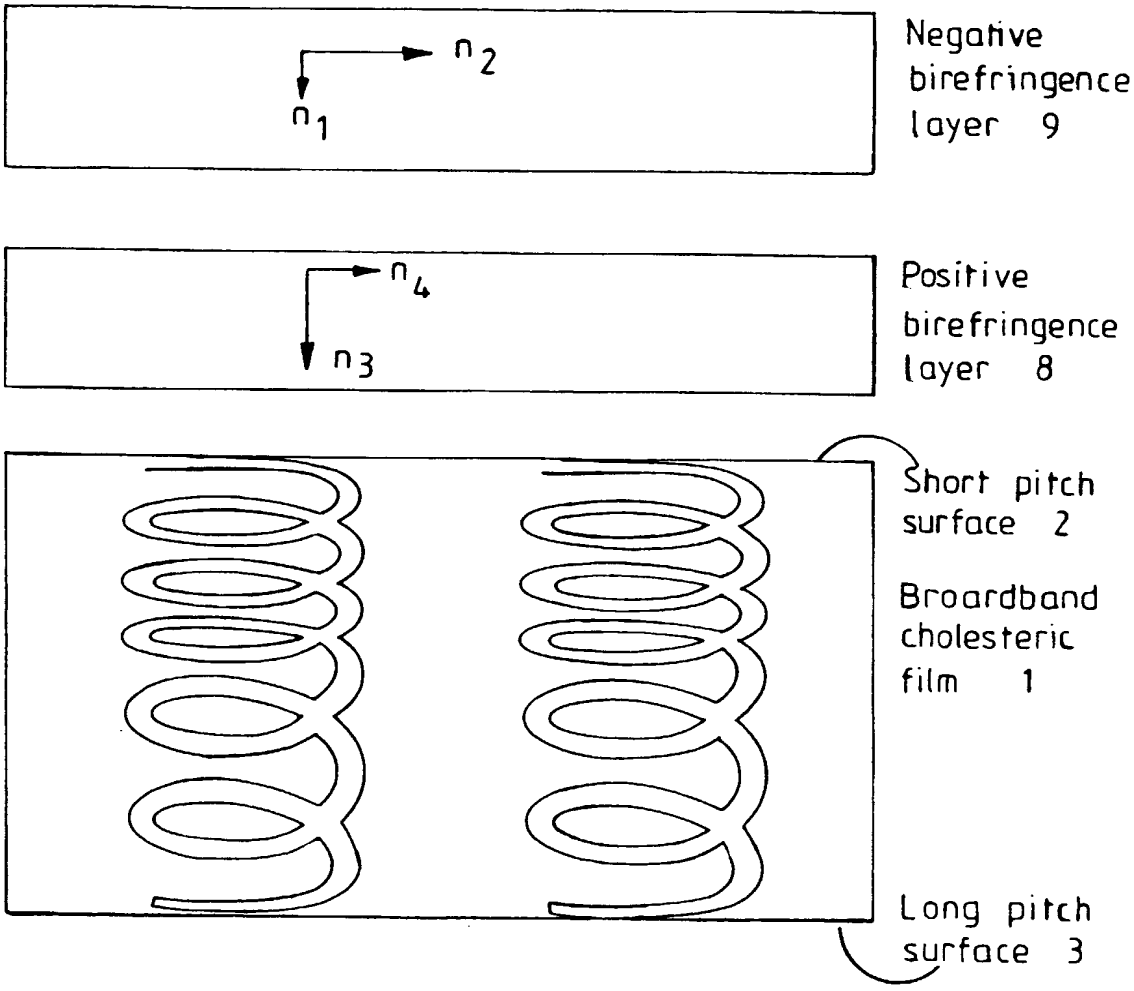

n2
n1
Negative birefringence layer 9
n4
n3
Positive birefringence layer 8
Short pitch surface 2
Broardband cholesteric film 1
Long pitch surface 3

FIG. 10

Double-film compensator placed next to the shortest pitch of the broadband cholesteric film, 0 degrees

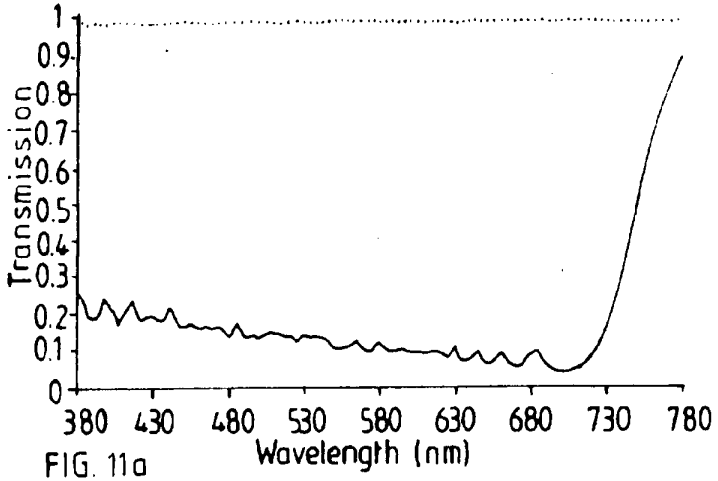


FIG. 11a

Double-film compensator placed next to the shortest pitch of the broadband cholesteric film, 15 degrees

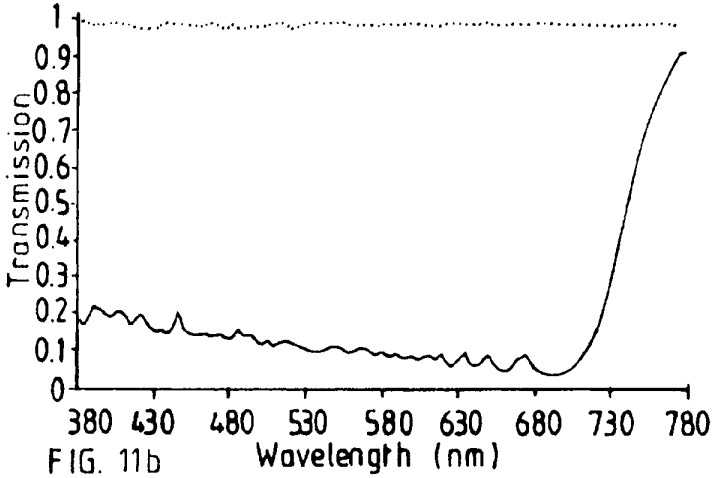


FIG. 11b

Double-film compensator placed next to the shortest pitch of the broadband cholesteric film, 31 degrees

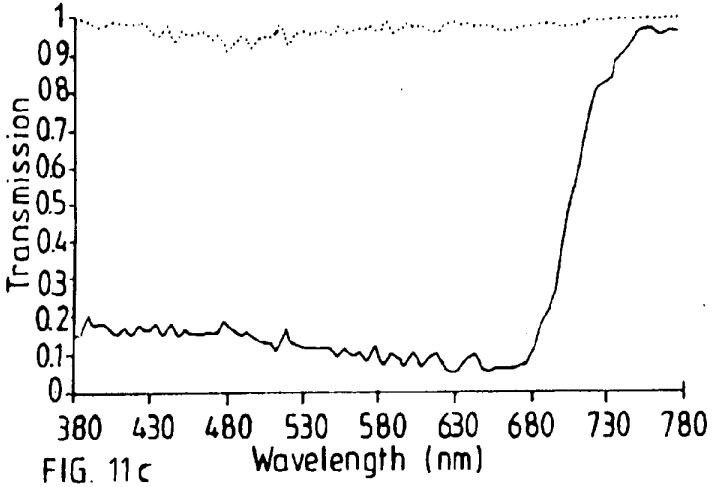


FIG. 11c

Double-film compensator placed next to the shortest pitch of the broadband cholesteric film, 49 degrees

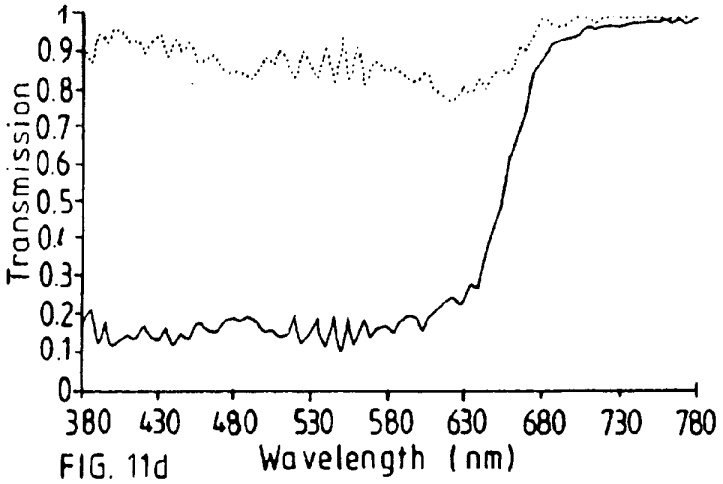


FIG. 11d

Short pitch to long pitch, no compensator, 0 degrees

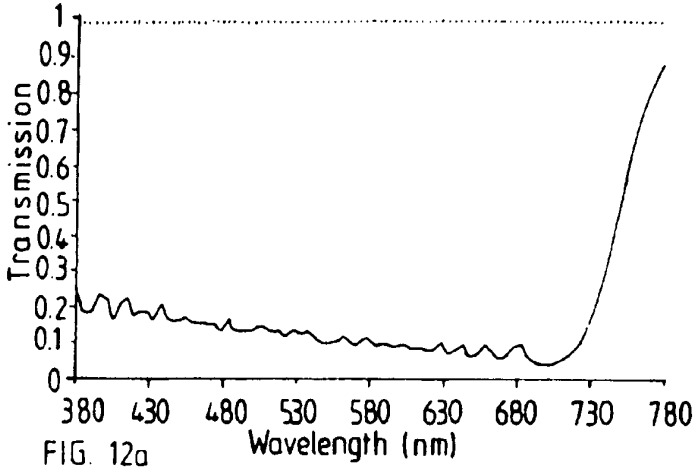


FIG. 12a

Short pitch to long pitch, no compensator, 15 degrees

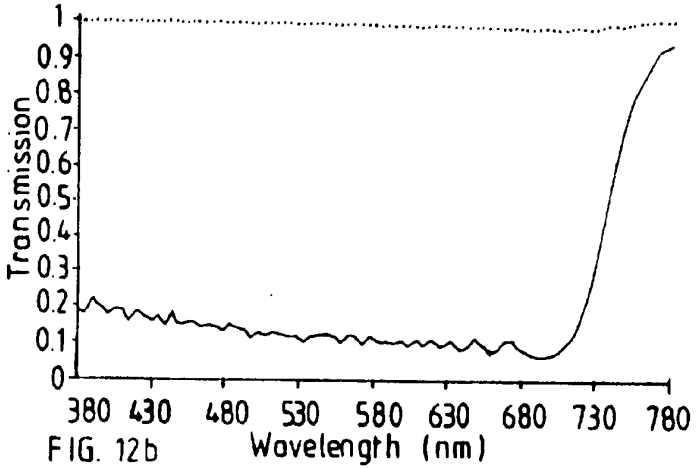


FIG. 12b

Short pitch to long pitch, no compensator, 31 degrees

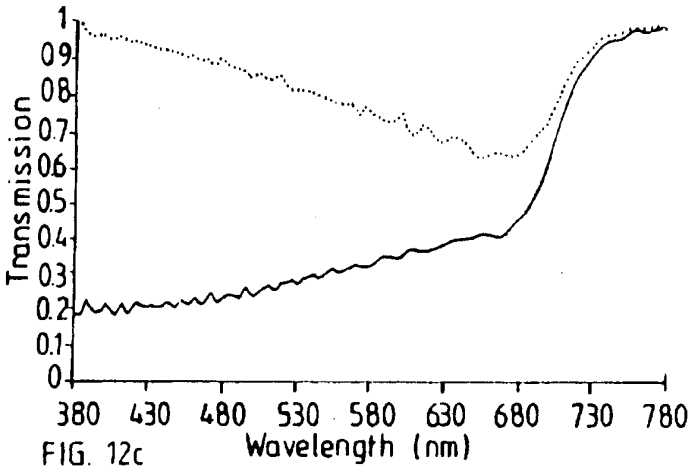


FIG. 12c

Short pitch to long pitch, no compensator, 49 degrees

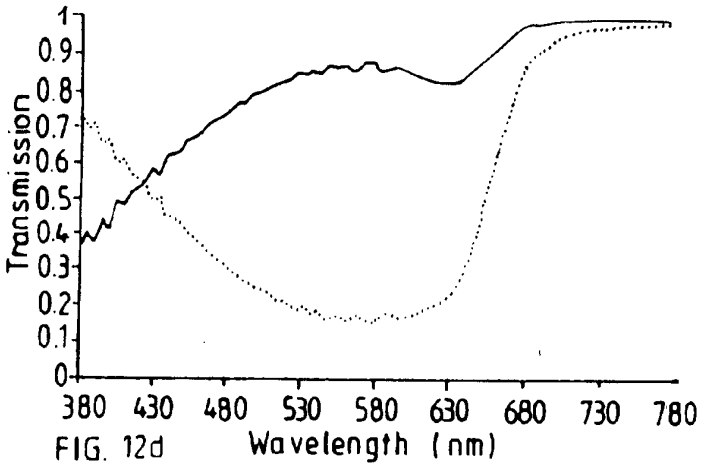


FIG. 12d

Double-film compensator placed next to the longest pitch of the broadband cholesteric film, 0 degrees

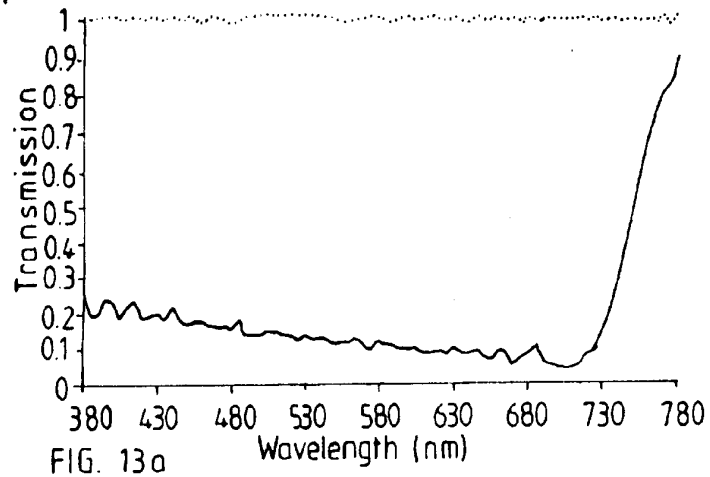


FIG. 13a

Double-film compensator placed next to the longest pitch of the broadband cholesteric film, 15 degrees

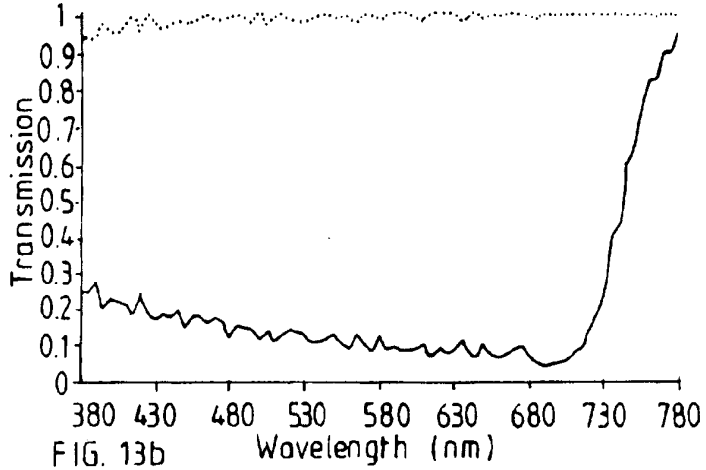


FIG. 13b

Double-film compensator placed next to the longest pitch of the broadband cholesteric film, 31 degrees

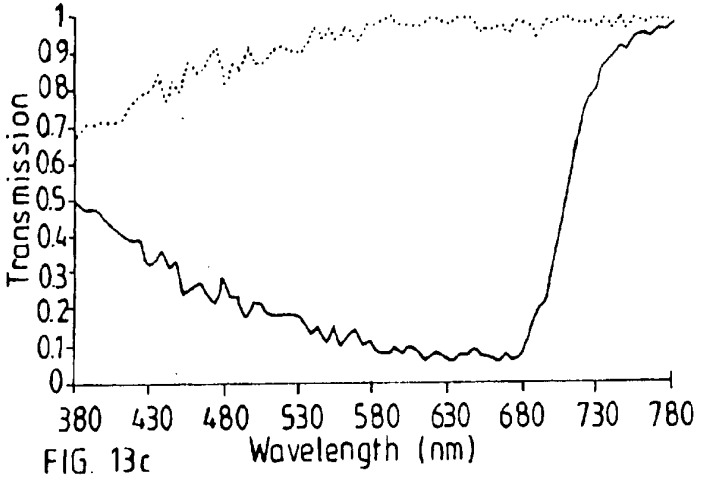


FIG. 13c

Double-film compensator placed next to the longest pitch of the broadband cholesteric film, 49 degrees

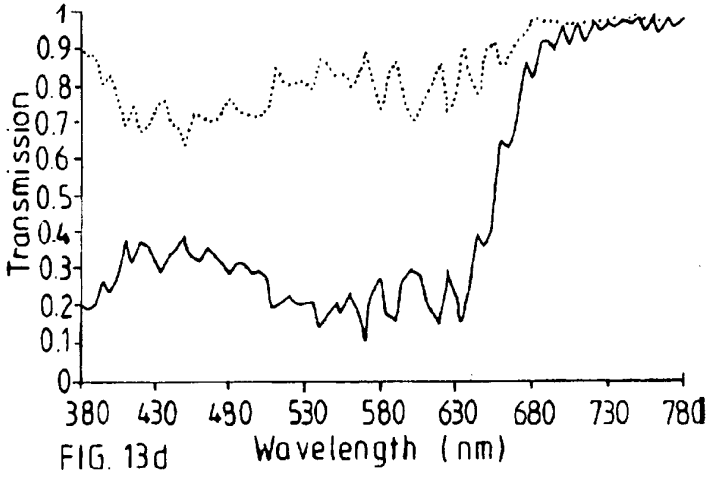


FIG. 13d

Long pitch to short pitch, no compensator, 0 degrees

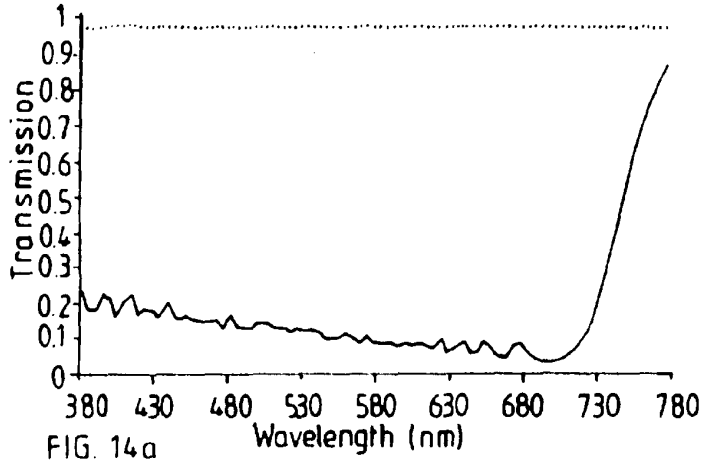


FIG. 14a

Long pitch to short pitch, no compensator, 15 degrees

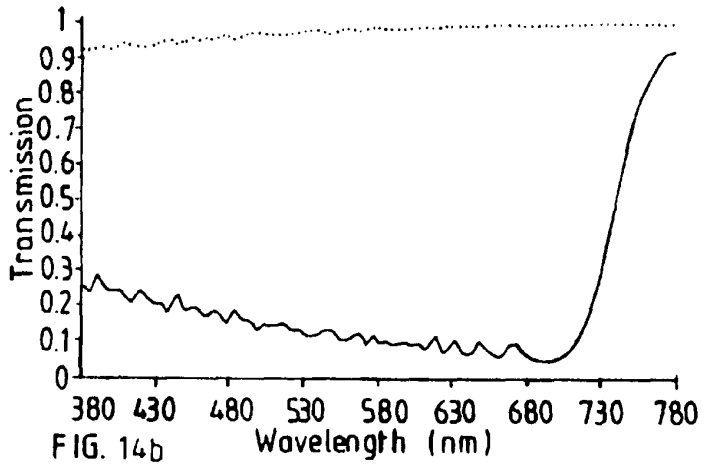


FIG. 14b

Long pitch to short pitch, no compensator. 31 degrees

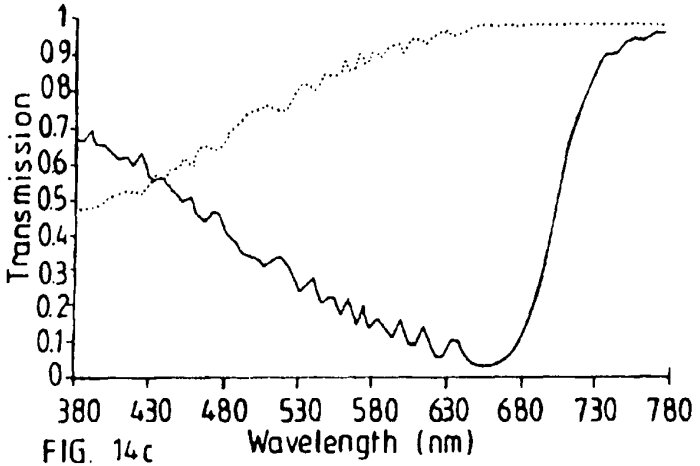


FIG. 14c

Long pitch to short pitch, no compensator, 49 degrees

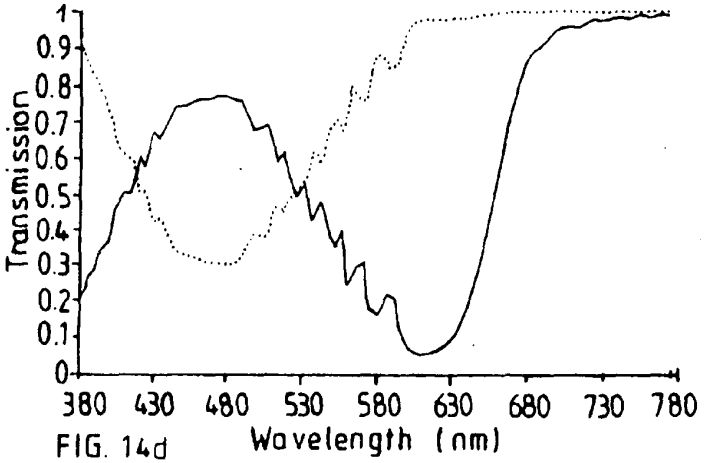


FIG. 14d

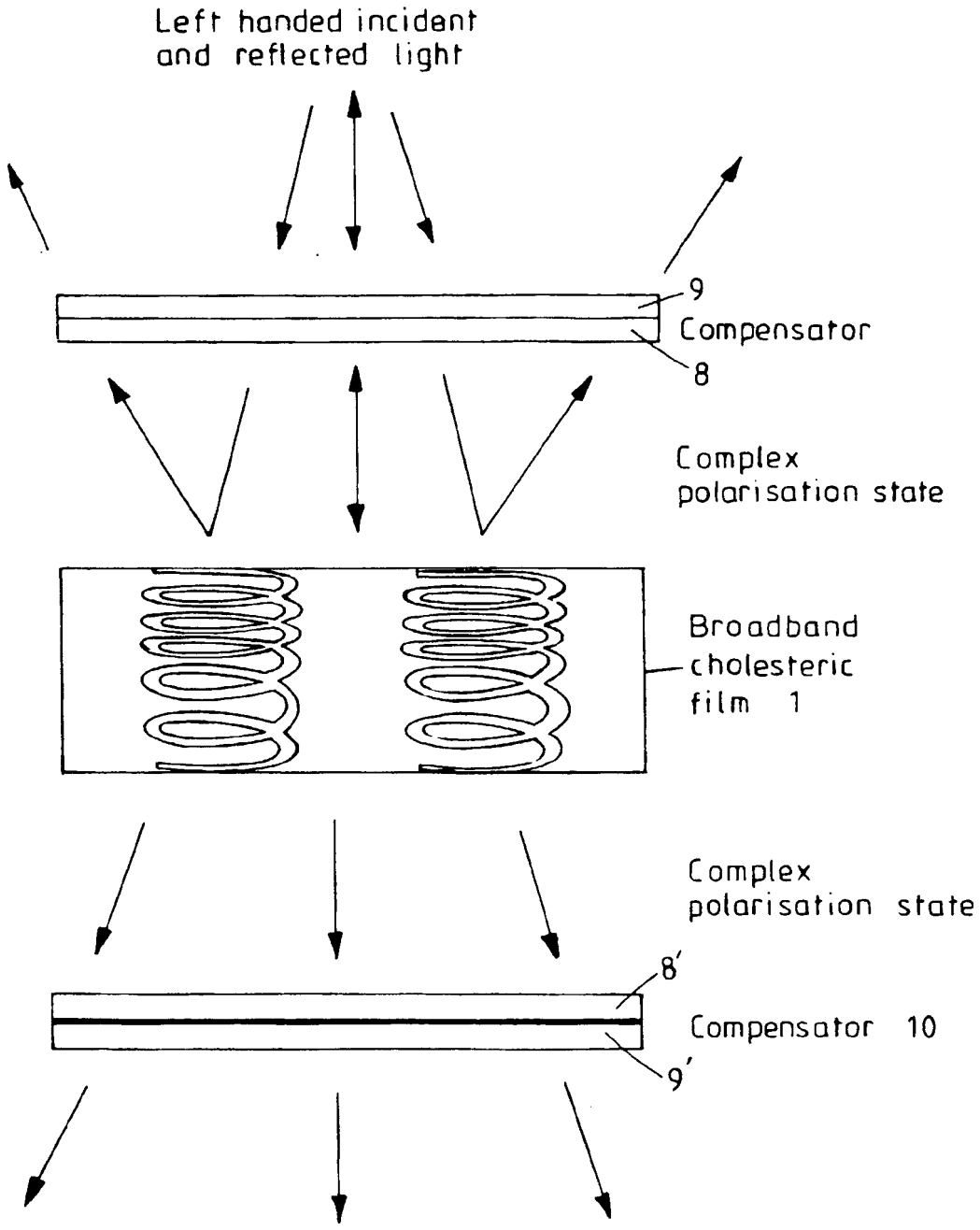

Left handed incident
and reflected light
9
Compensator
8
Complex
polarisation state
Broadband
cholesteric
film 1
Complex
polarisation state
8'
Compensator 10
9'
Transmitted right-handed light

FIG. 15

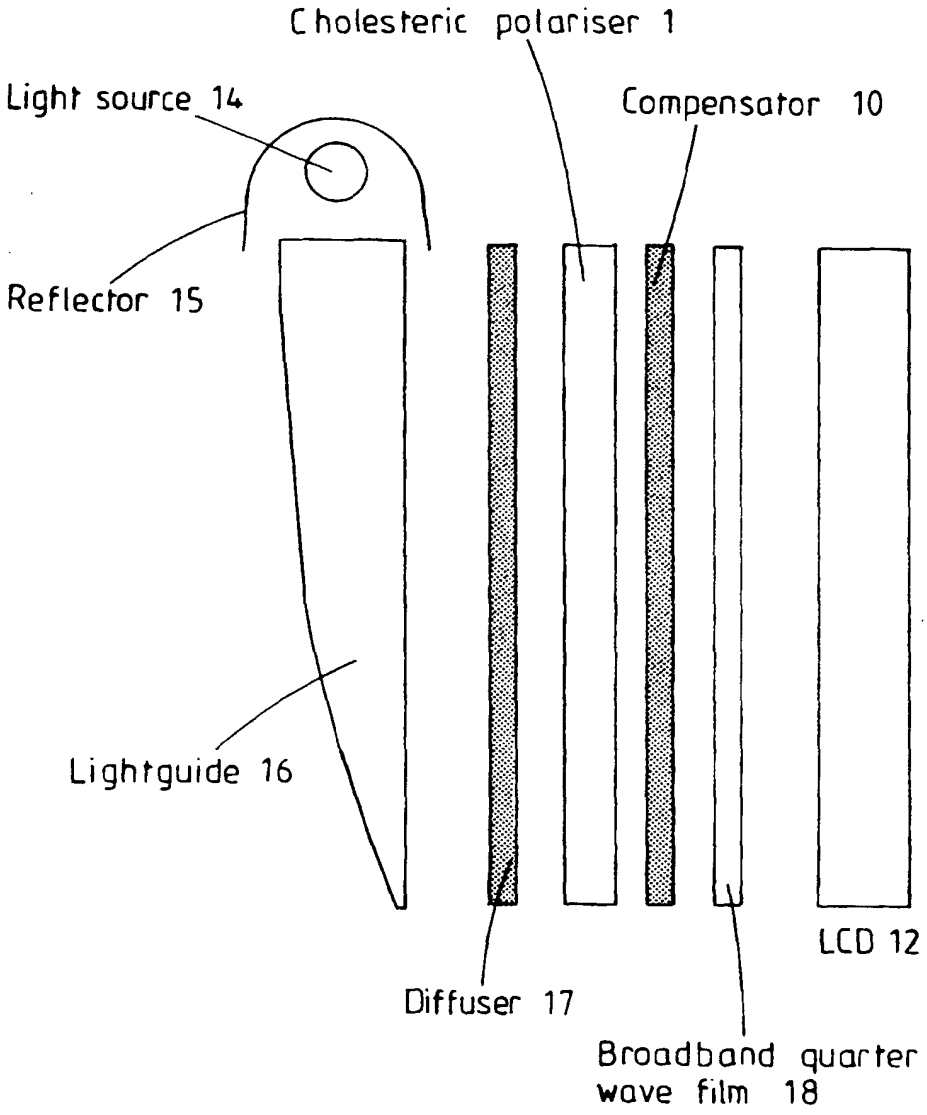

Cholesteric polariser 1
Light source 14
Compensator 10
Reflector 15
Lightguide 16
LCD 12
Diffuser 17
Broadband quarter wave film 18

FIG. 16

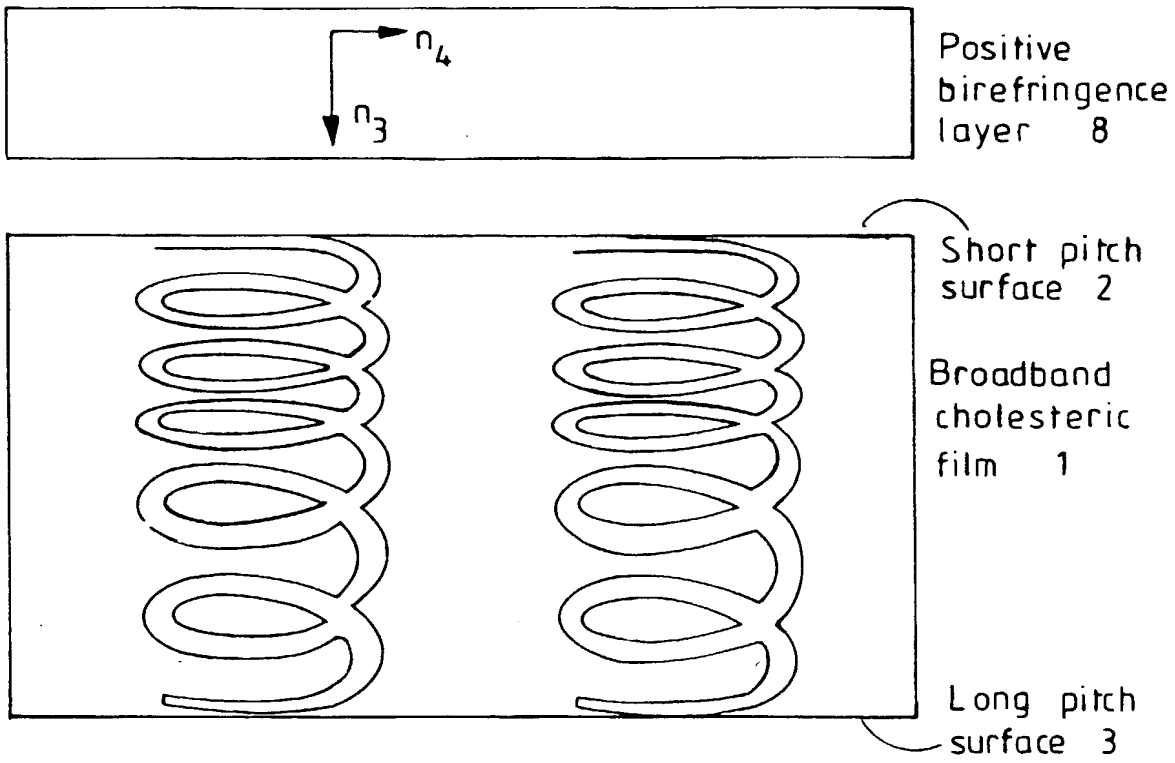

n_4
n_3
Positive birefringence layer 8
Short pitch surface 2
Broadband cholesteric film 1
Long pitch surface 3

FIG. 17

Single layer compensator placed next to the shortest pitch of the broadband cholesteric film, 0 degrees

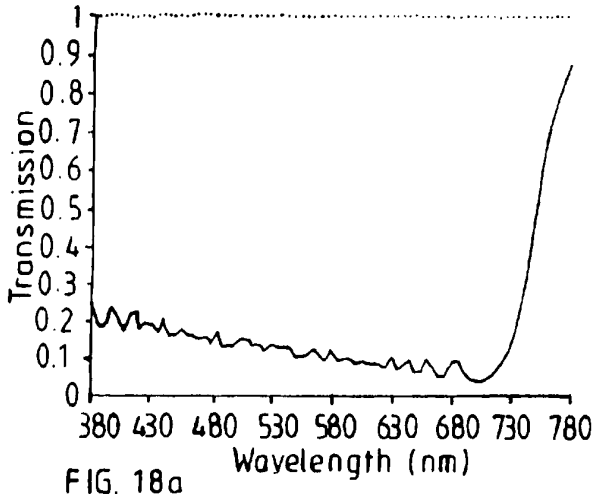


FIG. 18a

Single layer compensator placed next to the shortest pitch of the broadband cholesteric film, 15 degrees

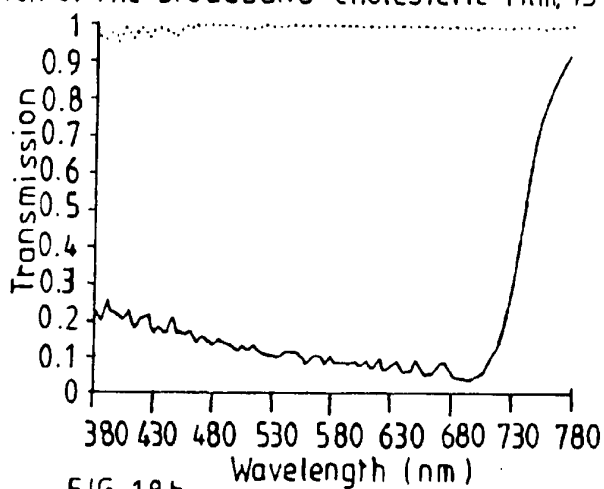


FIG. 18b

Single layer compensator placed next to the shortest pitch of the broadband cholesteric film, 31 degrees

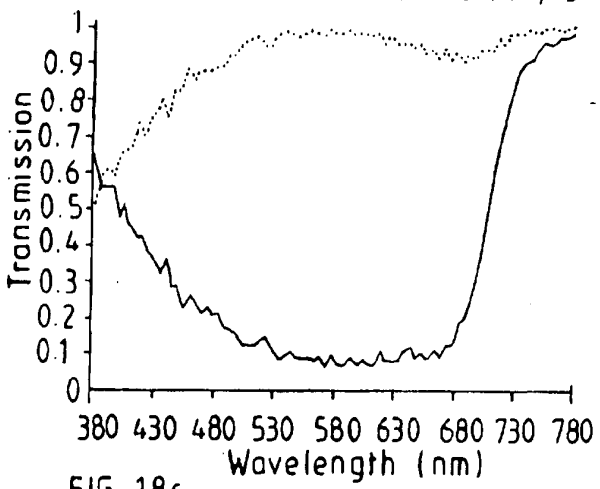


FIG. 18c

Single layer compensator placed next to the shortest pitch of the broadband cholesteric film, 49 degrees

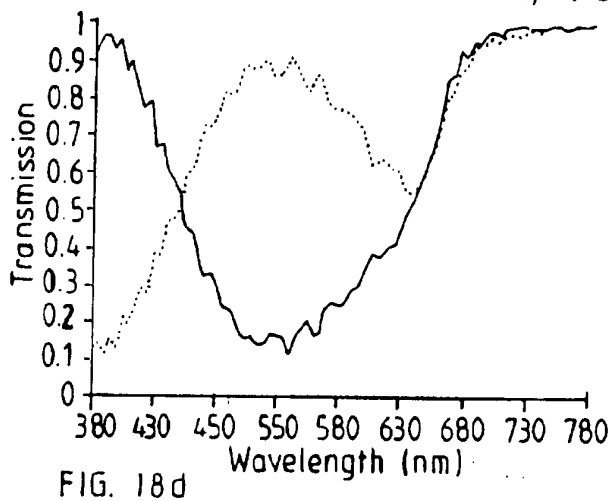


FIG. 18d

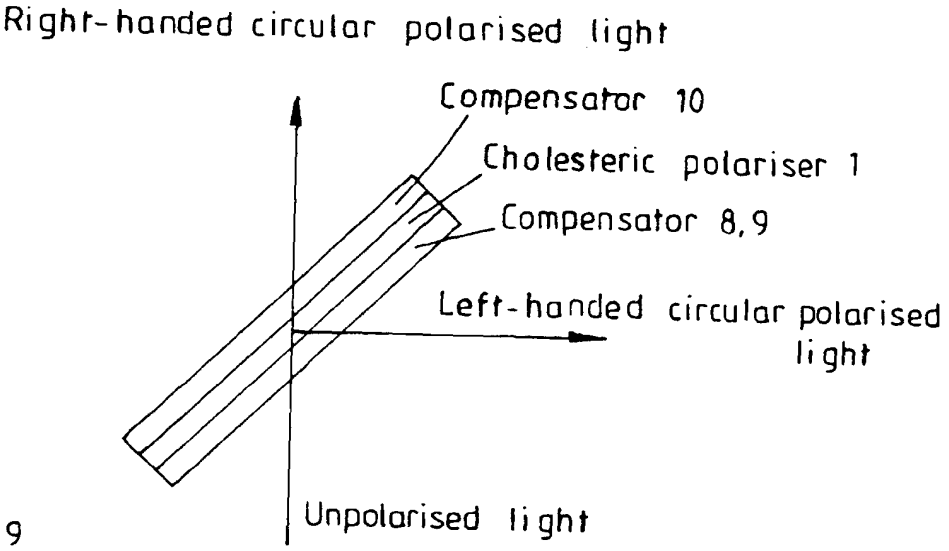

Right-handed circular polarised light
Compensator 10
Cholesteric polariser 1
Compensator 8,9
Left-handed circular polarised light
Unpolarised light

FIG. 19

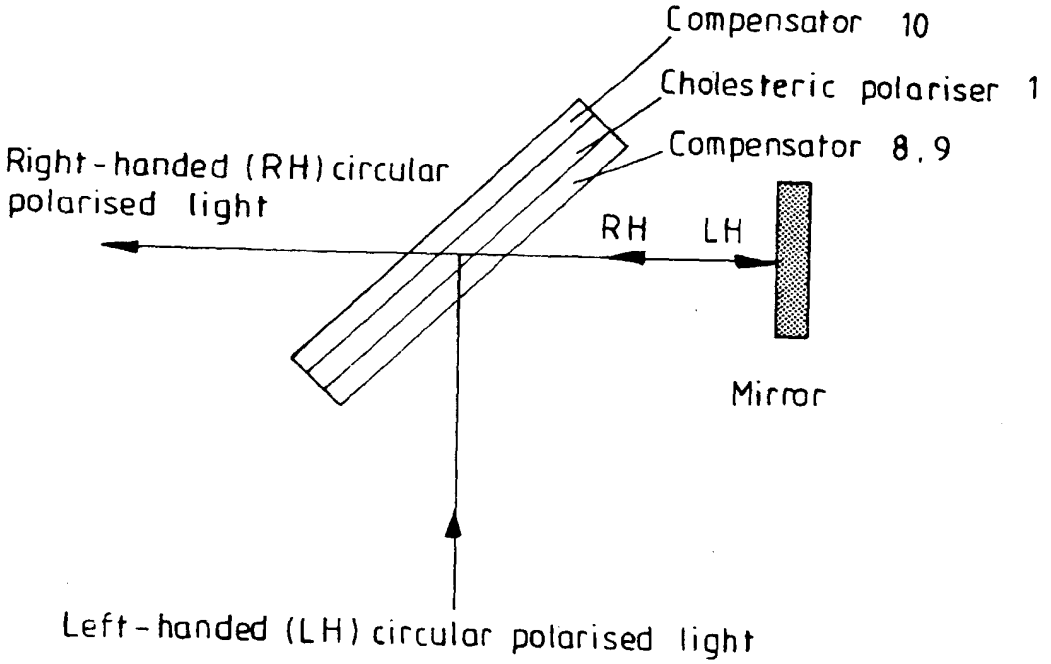

Compensator 10
Cholesteric polariser 1
Compensator 8,9
Right-handed (RH) circular polarised light
RH
LH
Mirror
Left-handed (LH) circular polarised light

FIG. 20

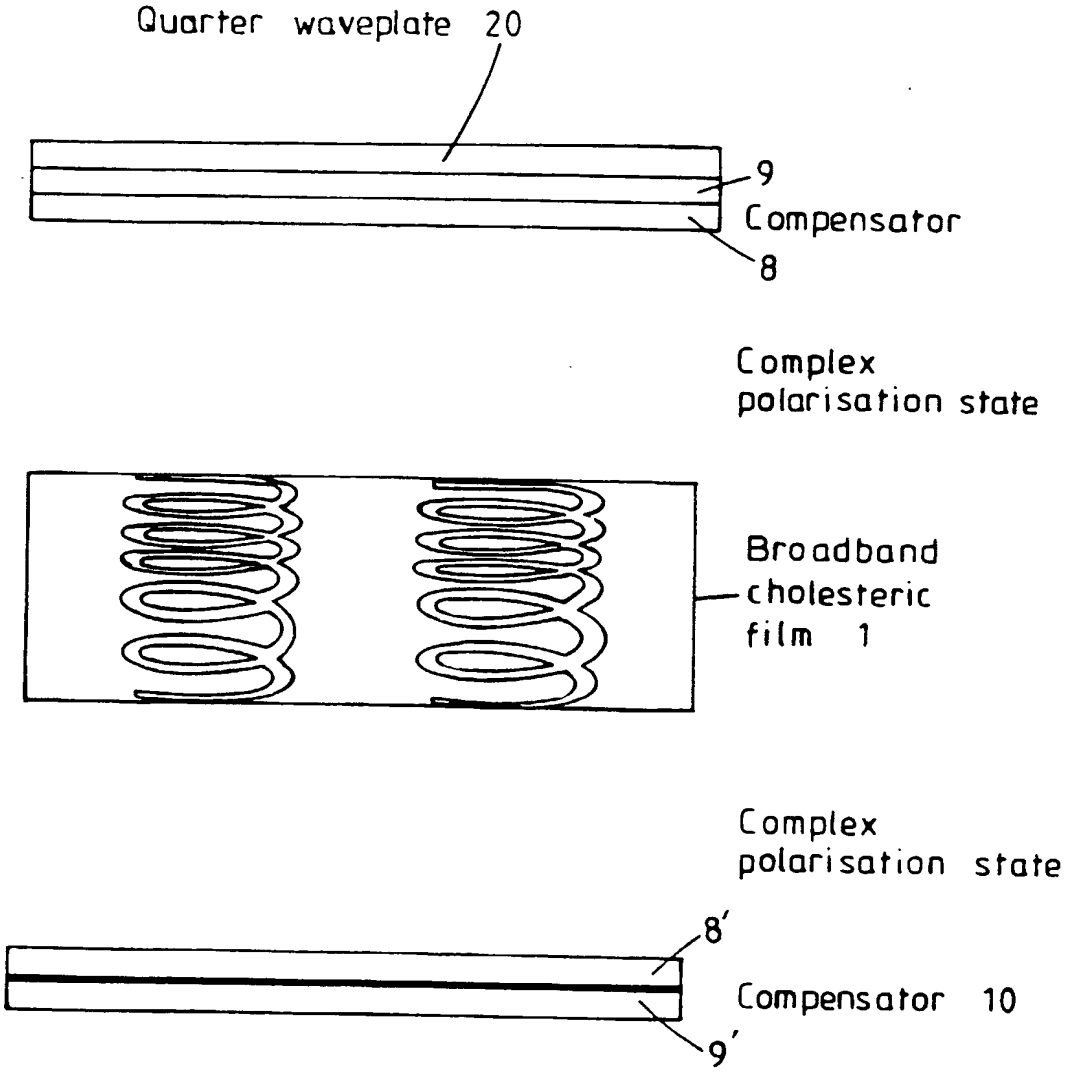

Quarter waveplate 20
9
Compensator
8
Complex
polarisation state
Broadband
cholesteric
film 1
Complex
polarisation state
8'
Compensator 10
9'

FIG. 21

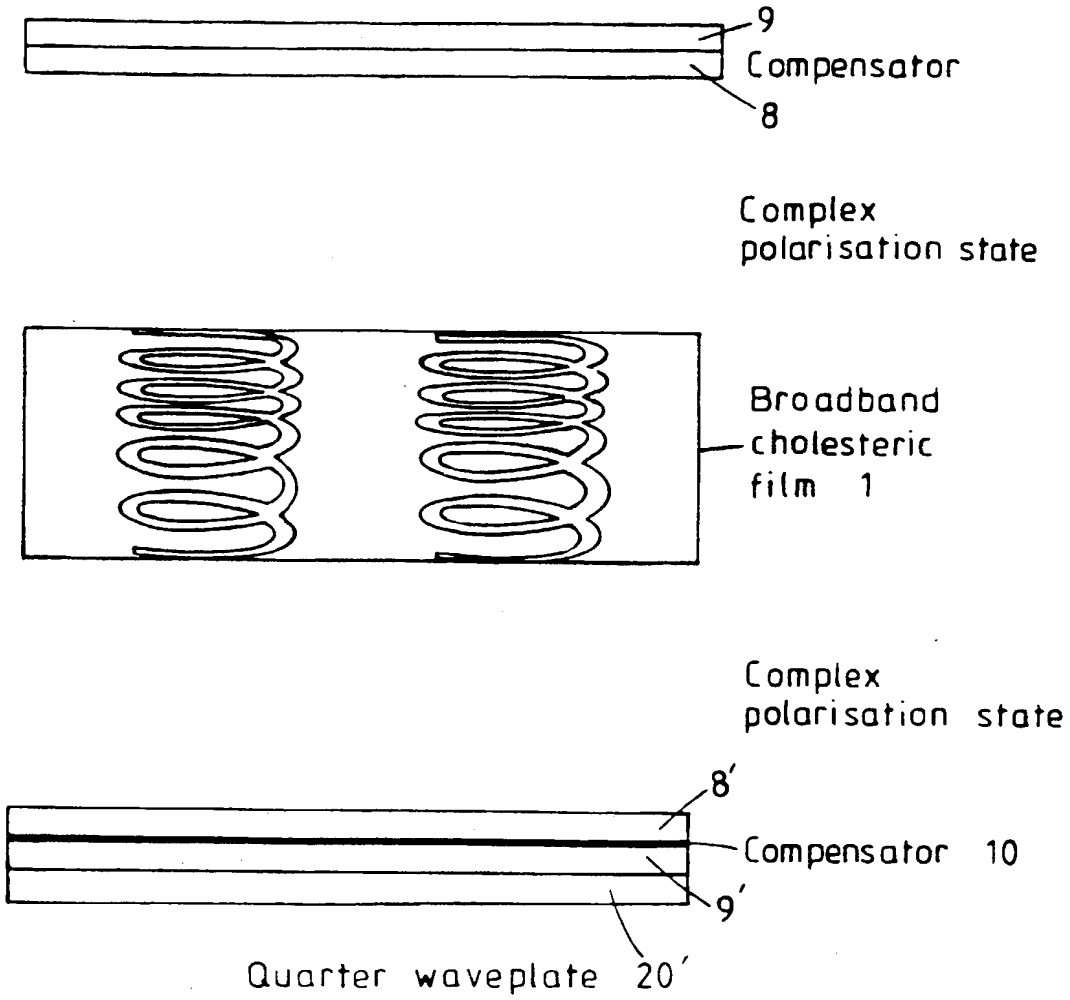

9
Compensator
8
Complex
polarisation state
Broadband
cholesteric
film 1
Complex
polarisation state
8'
Compensator 10
9'
Quarter waveplate 20'

FIG. 22

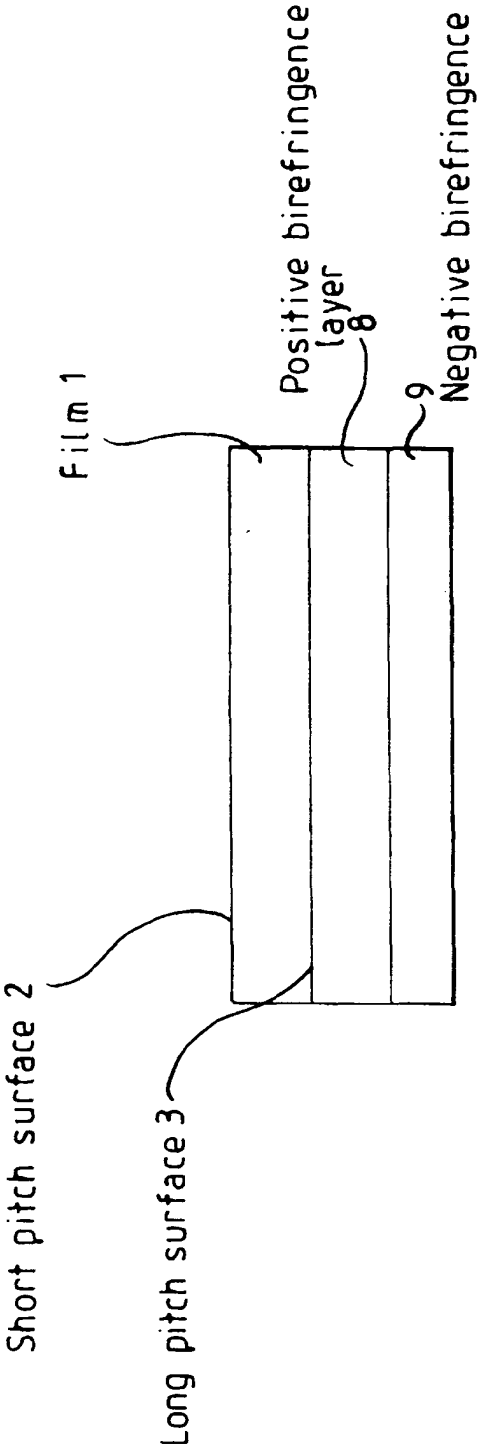

Film 1
Positive birefringence layer 8
9
Negative birefringence
Short pitch surface 2
Long pitch surface 3

FIG 23

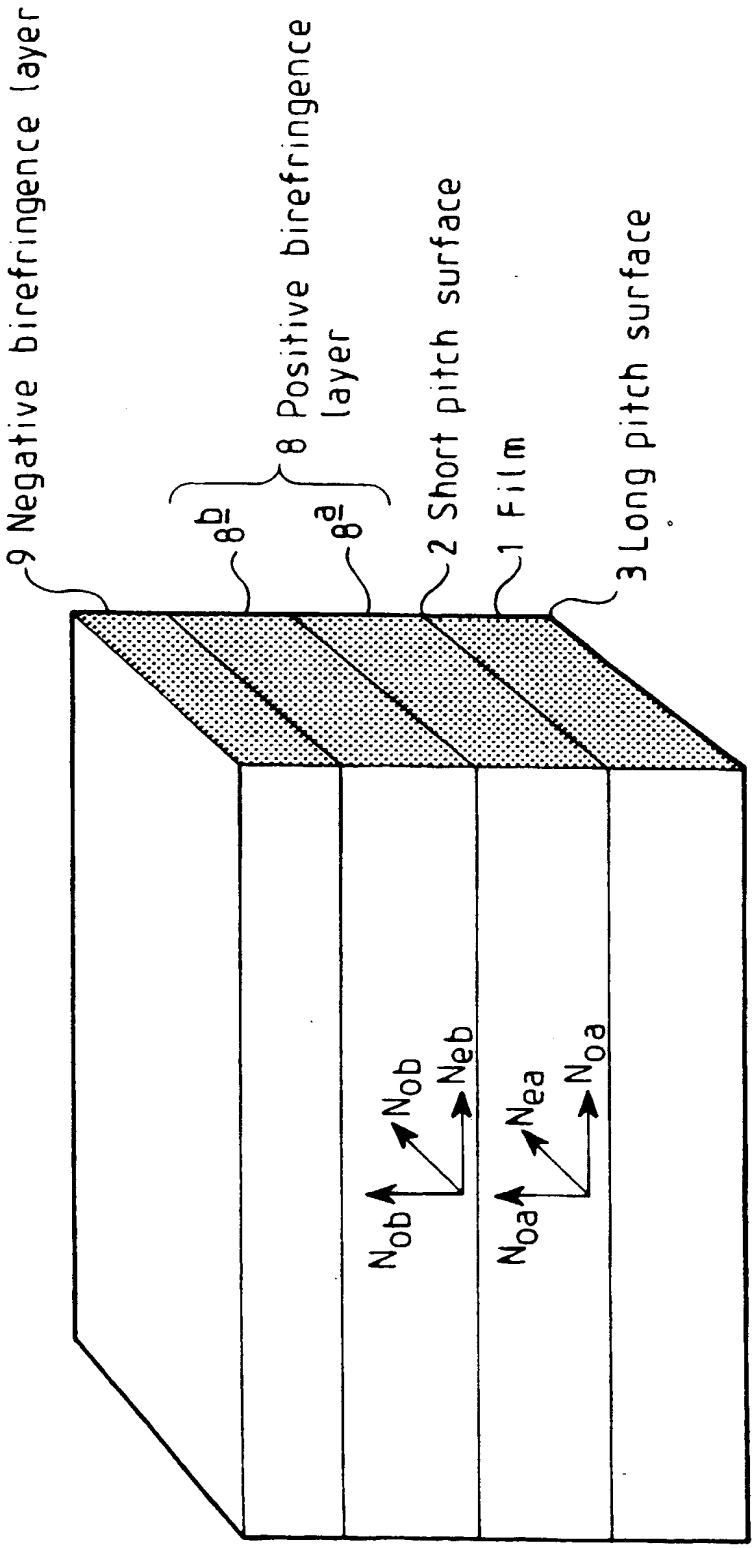
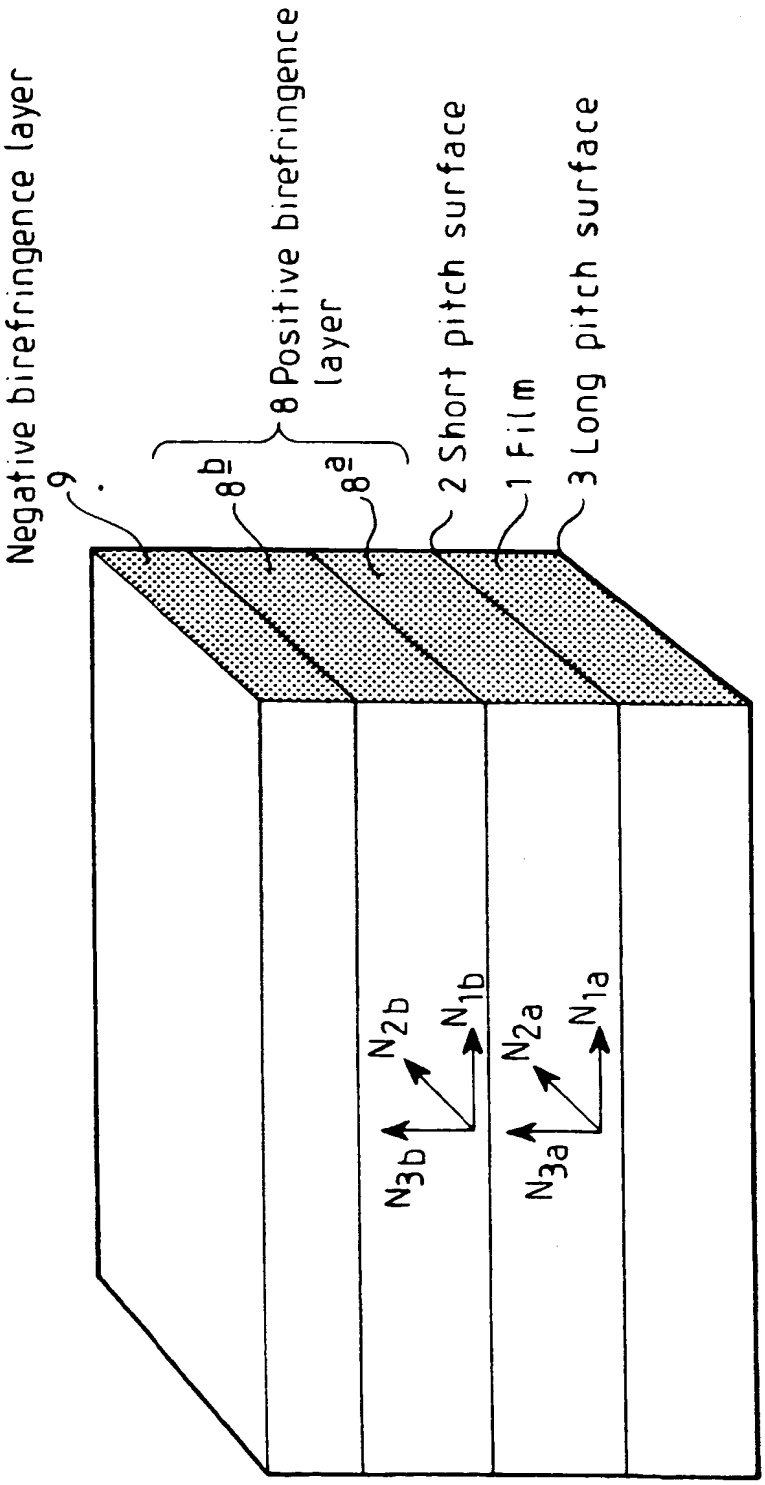

9 Negative birefringence layer
8 Positive birefringence layer
8^b
8^a
2 Short pitch surface
1 Film
3 Long pitch surface
N_{ob}
N_{eb}
N_{ea}
N_{oa}
N_{ob}
N_{oa}

FIG 24

FIG 25


Negative birefringence layer
9
8 Positive birefringence layer
8b
8a
2 Short pitch surface
1 Film
3 Long pitch surface
N2b
N1b
N3b
N2a
N1a
N3a

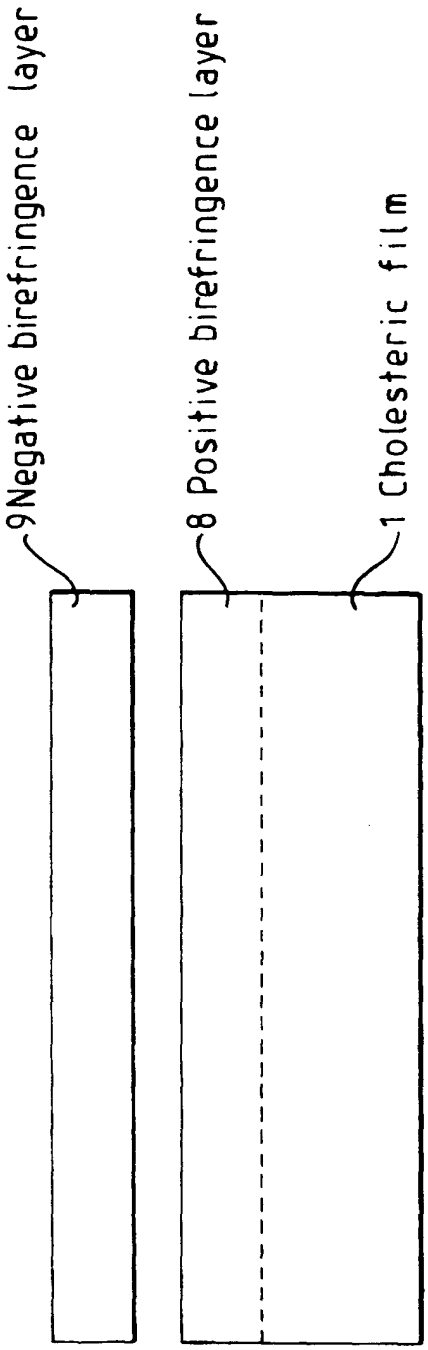

9Negative birefringence layer
8 Positive birefringence layer
1 Cholesteric film

FIG 26

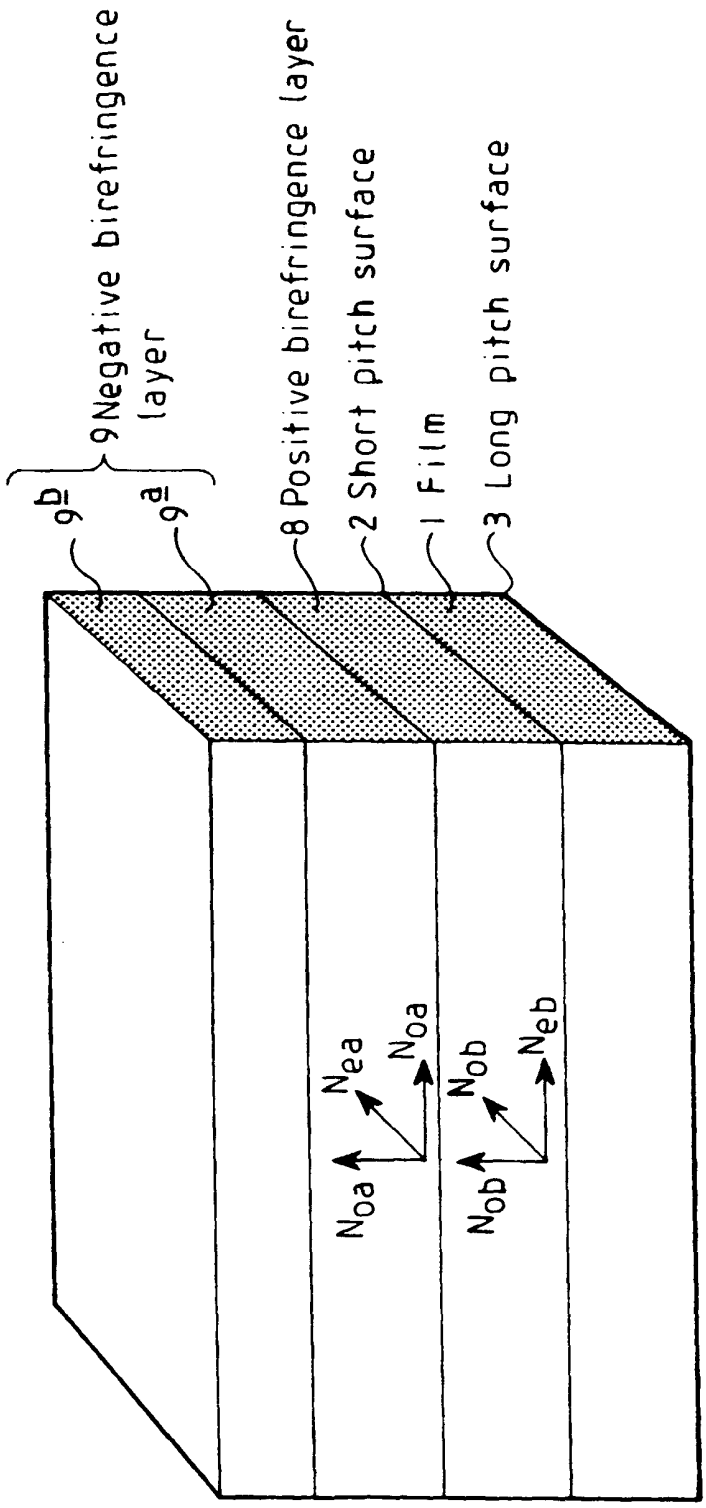

9 Negative birefringence layer
9b
9a
8 Positive birefringence layer
2 Short pitch surface
1 Film
3 Long pitch surface
Nea
Noa
Noa
Nob
Neb
Nob

FIG 27

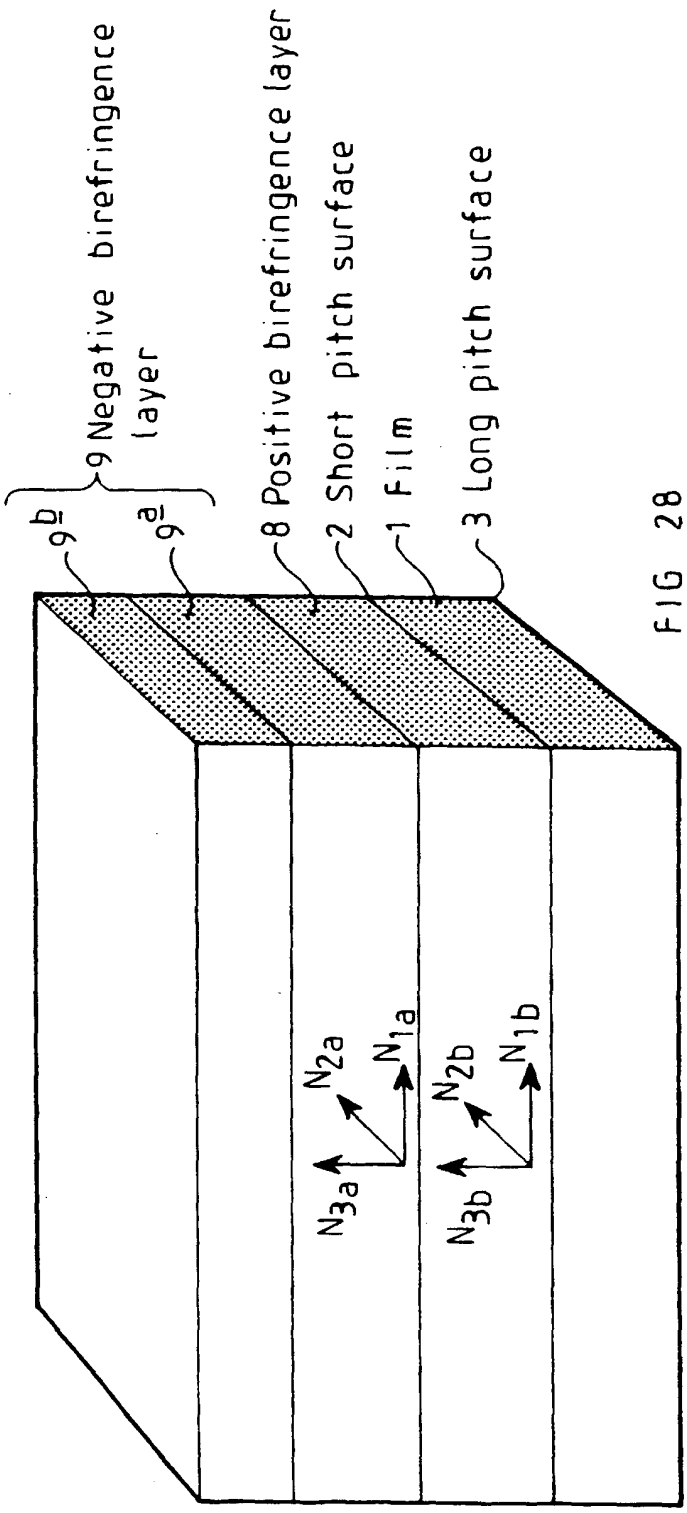

9 Negative birefringence layer
9b
9a
8 Positive birefringence layer
2 Short pitch surface
1 Film
3 Long pitch surface
N2a
N1a
N3a
N2b
N1b
N3b

FIG 28

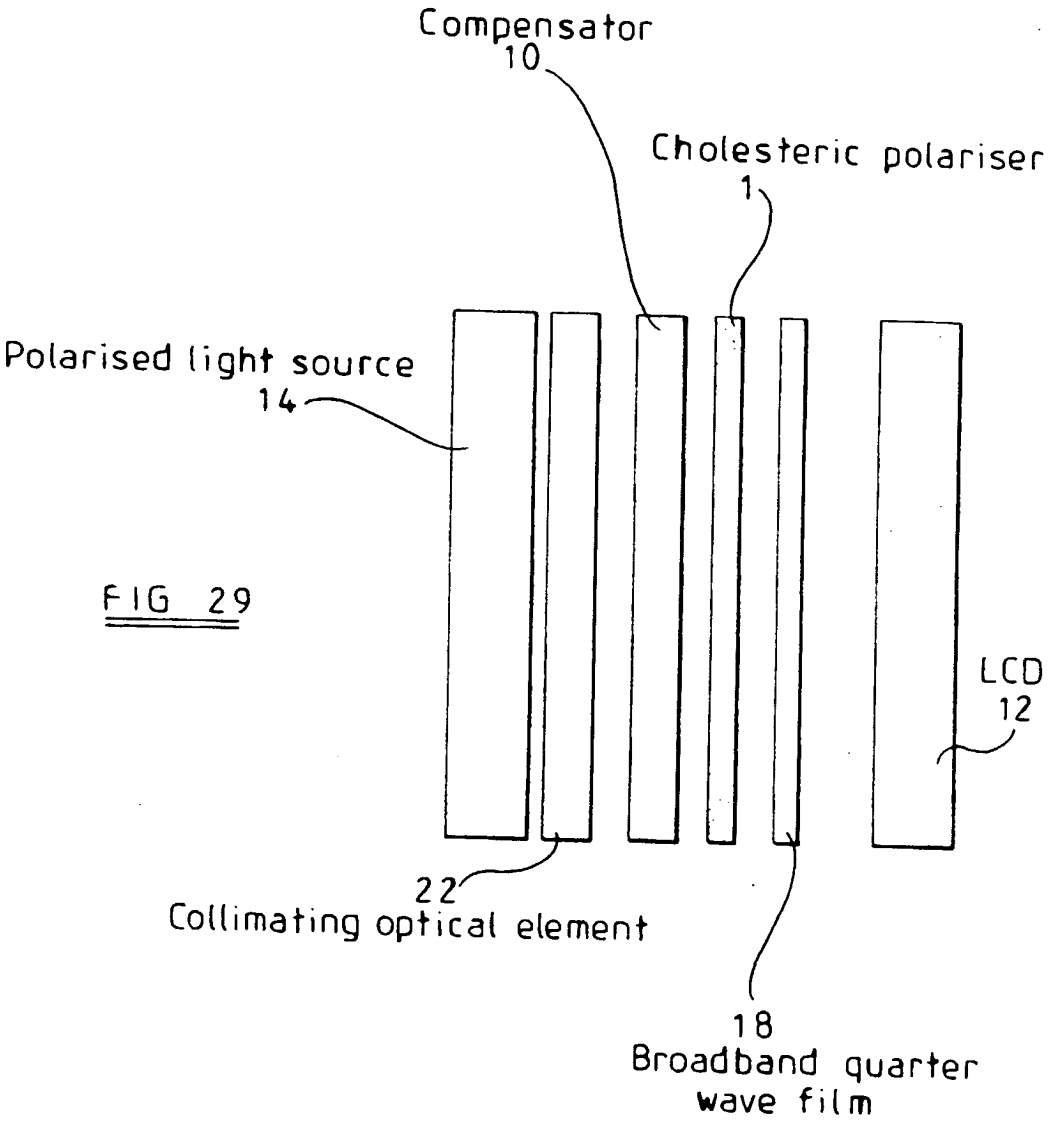

Compensator
10
Cholesteric polariser
1
Polarised light source
14
LCD
12
22
Collimating optical element
18
Broadband quarter
wave film

FIG 29

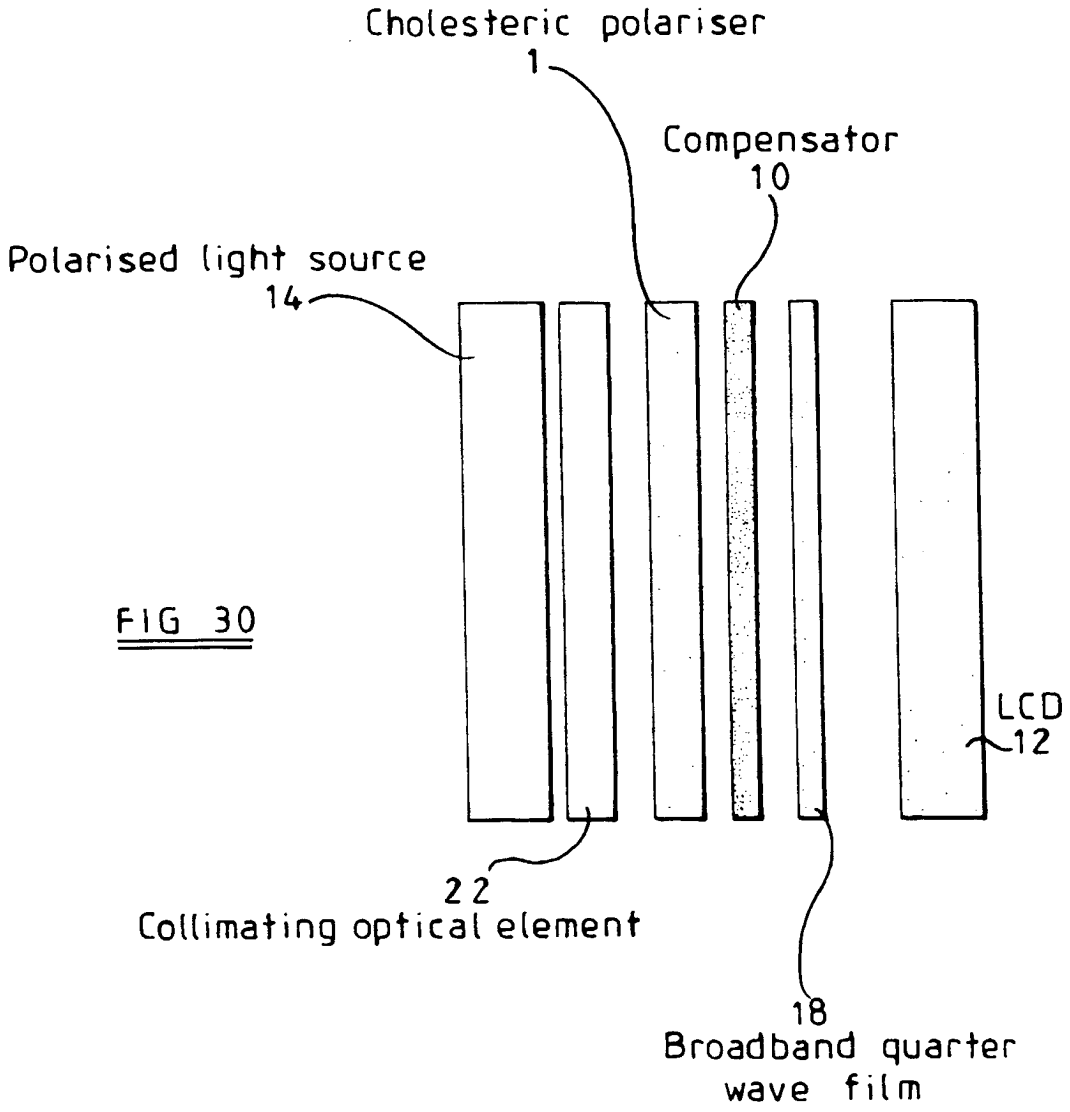

Cholesteric polariser
1
Compensator
10
Polarised light source
14
LCD
12
22
Collimating optical element
18
Broadband quarter
wave film

FIG 30

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(54) Broadband cholesteric optical device, polariser, filter, Liquid crystal device and polarising beam-splitter

(57) A broadband cholesteric optical device such as a polariser or spectral filter comprises a broadband cholesteric layer 1, for instance of the graded pitch type such that the cholesteric pitch increases monotonically from one surface 2 of the film 1 to the other 3. In order to improve the off-axis performance, a compensator is provided in the form of a positive birefringence film 8 whose optic axis is substantially perpendicular to the film. Another negative birefringence film 9 whose optic axis is also perpendicular to the film may also be provided.

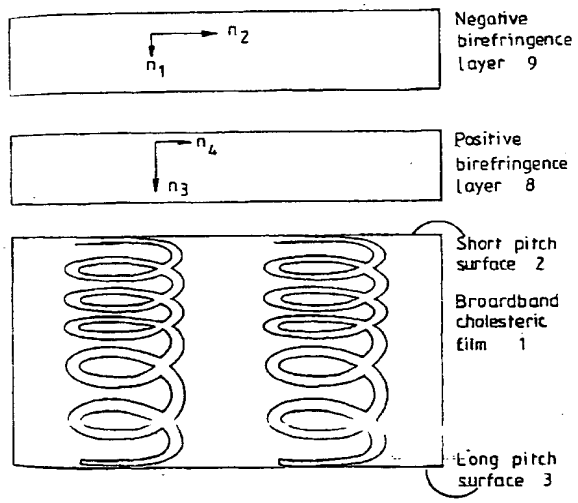

FIG. 10

EP 0 860 717 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 98 30 0477

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
E	US 5 731 886 A (GUNNING III WILLIAM J ET AL) 24 March 1998 * column 2, line 29 - line 34 * * column 2, line 55 - line 62 * * column 4, line 56 - column 5, line 10; claim 1 *	1,3-5	G02B5/30 G02F1/1335
D,A	EP 0 606 940 A (PHILIPS ELECTRONICS NV) 20 July 1994 * page 3, line 8 - line 58; claim 1; figure 1 *	1	
A	EP 0 606 939 A (PHILIPS ELECTRONICS NV) 20 July 1994 * abstract; figure 1 *	1	

TECHNICAL FIELDS SEARCHED (Int.Cl.6)

G02B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	11 August 1998	Hervé, D

CATEGORY OF CITED DOCUMENTS

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